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H-3-13

MEMORANDUM TO: W. B. Drake
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SUBJECT: Research Report 535; "Occurrences of Expansive Limestone in Kentucky;" KYP-64-13; HPR-PL-1(15), Part III B.

Durable rock is a precious resource. Sometimes, stone for masonry and aggregates is presumed to be durable when it is not. Too frequently, porous gravels and ledgerock have proved later to be unworthy of high service -- to the loss of the builder and(or) the owner. In the contexts here, it is the impurity of some limestone ledgerocks which spoils the lot unless isolated. Clayey limestones -- usually slightly dolomitic -- decompose when exposed to weather. Expansion occurs inside concrete and ruins otherwise durable structures. In the case of aggregates for concrete, the issue becomes: How much of the deleterious rock is tolerable and allowable? This question incites another: How long is the structure expected to endure?

Whereas assurances of durability may be sought in histories of performance in structures, observations of natural exposures of rock ledges in bluffs and exposures in highway cuts are usually more revealing of offending ledges or beds. Resistance to weathering may be tested by exposing ledgerock specimens in fields, yards, or on decks where observations and records of endurance may be kept.

Research Report 325, "Expansive Limestone Aggregate in a Concrete Pavement," April 1972, remains a worthy, preliminary treatise on the two, principal roles of limestone aggregates in the premature deterioration of concrete. The role addressed more directly here, and there, is the expansion of clayey dolomitic limestones. The other role, of course, is freezing and thawing of porous, nearly saturated, otherwise non-expansive, aggregate in the concrete. Report 287 ("Freeze-and-Thaw Phenomena in Concretes and Aggregates," February 1970), Report 454 ("Freeze-and-Thaw of Concrete and Aggregates," June 1976), and Report 460 ("Possible Explanation of Concrete Popouts," Research Record 651, Transportation Research Board, Washington, D.C.; 1977) treat those characteristics of aggregates and the deteriorating mechanisms more specifically. Report 445, "The D-Cracking Phenomenon: A Case Study for Pavement Rehabilitation" (April 1976) and Report No. 480, "Cracking in Continuously Reinforced Concrete Pavements" (October 1977), explain two mechanisms of pavement deterioration which are not directly attributable to defects in the quality of aggregates. Similar reference is made to Report 529, "Cracking in Concrete Pavements" (October 1979), consigned to American Society for Civil Engineers for publication.

The survey of quarries and the testing of ledgerock was done by Mr. Coy under David L. Arnall, formerly Chief Geologist, in the Division of Materials. Mr. Arnall's "retirement" preceded issuance of this report. Because of his many years of dedication to the assurance of quality in aggregates, this report is given commemorative status. Mr. Arnall's reports on "Kentucky Aggregates" -- containing quarry logs and chemical compositions and physical properties -- dating from 1954 -- were helpful in selectively sampling ledges exhibiting attributes identifying potentially expansive rock. Approximately 2,600 thin sections were made and examined. Mr. Coy transferred to the Department of Natural Resources in May 1979.

It is desirable to be able to associate unsoundness with properties and composition and also with appearance, texture, and geological occurrence. Texture has been illustrated here and elsewhere. Scanning electron micrographs included here have some special qualities and significance not recognized heretofore.

The value of this research and these reports surely will extend beyond the imminent guidance of policy decisions and the establishment of safeguarding-procedures and specifications. Indeed, the work contributes significantly to the scientific knowledge of rock and building stones.

The most direct and immediate benefits will be, of course, the avoidance of recurrences of premature disintegration of concrete -- and may thereby restore the assurances of unlimited life-expectancy of concrete structures.

Respectfully submitted,

Jas. H. Havens

Jas. H. Havens
Director of Research

John E. McChord

John E. McChord
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Enclosure
cc's: Research Committee

Research Report
-535-

OCCURRENCES OF EXPANSIVE LIMESTONE IN KENTUCKY

KYP-64-13 HPR-PL-1(15),Part III B

by

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Bureau of Highways
DEPARTMENT OF TRANSPORTATION
Commonwealth of Kentucky

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SAMPLING AND APPROVAL OF AGGREGATE SOURCES

The Commonwealth of Kentucky approves or disapproves a proposed source of limestone aggregate in the following way: the producer-operator of the quarry notifies the District Materials Engineer who, in turn, notifies the Central Materials Laboratory (or the Aggregate Control Section at the Central Materials Laboratory may be notified directly) when approximately 25 feet (8 m) or more of stone has been uncovered and faced for sampling. A geologist then examines the exposed face, foot by foot, for lithologic changes such as changes in color, grain size, etc. Each change is noted in the geologist's field records. Each change in lithology is designated as a distinct ledge, and an attempt is made to maintain workable, physical units (shale seams, mud partings, geologic age, location, etc.) (see Appendix A) in the sampling and in the finished report. Approximately 100 pounds (45 kg) of stone are taken from each ledge in the quarry and carried to the Central Materials Laboratory. Sodium sulfate soundness, Los Angeles wear, specific gravity, and absorption are run in the aggregate laboratory; $CaCO_3$, $MgCO_3$, insoluble residue, R_2O_3 (metal content), and SiO_2 are determined by the Chemical Section. When the tests are completed, a report called the "Quarry Log" is prepared by the Aggregate Control Section; it includes all the mentioned information and an approval number. Each ledge must be tested for the quality requirements for soundness and wear, and each ledge is designated thereon as "passing" or "failing".

Currently over 117 active quarries are approved. There are approximately 1,300 ledges. Thus, approximately 1,300 different lithologic samples are necessary to make a comprehensive study of all the ledges reported by the Division of Materials, Central Laboratory.

INITIAL CONCERN

The necessity for an extensive investigation into the potential reactivity of limestone aggregate resulted from the findings of the Division of Research in its investigation of blowups and unusual cracking of the concrete pavement constructed as I 65-1(13)13, Warren-Simpson Counties, in 1965 (1). The Report, "Expansive Limestone Aggregate in a Concrete Pavement," April 1972, provides details of that investigation and report of findings. Excerpts follow:

> "The affected pavement begins at Station 696 + 75 on Project I 65-1(17)6 which, at Station 735 + 65.4 northward (Simpson-Warren County Line) equates to Station 0 + 00, the beginning of I 65-1(13)13, and continues northward in Warren County to Station 450 + 00 (in the US 231 interchange) -- a distance of 9.26 miles. The Drakes Creek bridges are between Stations 702 + 00 and 704 + 25 in Simpson County.... Paving began June 10, 1965, at Station 450 + 00 and proceeded southward in the northbound lanes. No cracking or blowups have been found north of Station 450 + 00... (cracking of a lesser degree continues south of Station 696 + 75 in Simpson County).
>
> "The first blowup occurred May 9, 1966 -- at Station 319 + 10 (southbound). The second occurred on or about June 14, 1966 -- at Station 224 + 00 (northbound). Apparently, the crack pattern was not discovered until the summer of 1967. Installation of a regular series of relief joints was begun in the spring of 1968 but was later discontinued. Blowups occurred while sawing relief joints. No blowups occurred during 1969, but two occurred in 1970 -- one was a repeat occurrence; none occurred during 1971. Additional relief joints were installed near the Drakes Creek bridges -- where the pressure of the pavement apparently sheared the abutment wall of the bridge".

Following the research report, much concern was expressed within the Bureau of Highways over the possibility of a recurrence of this type of phenomenon in concrete performance on subsequent projects, and a specification was proposed to minimize the problem. However, at this point, the overall impact and consequences of implementation could not be foreseen. Uniform and equitable application of any requirements would be difficult because of the time involved in obtaining data on sources statewide. The Division of Materials recommended delay of implementation of the specifications until survey data could be obtained and an analysis made of the situation. The Division of Materials was delegated this responsibility in January 1973; and the Geology-Aggregate Section was assigned the testing program. It was evident that sampling and testing of all limestone sources approved to furnish material to Kentucky highway projects would be very time consuming: three to five years was the estimated time for completion.

With the threat of recurrence of the problem prior to completion of testing all sources, it was desirable to investigate sources on a priority basis. Information (1, 2, 3, 4) immediately available indicated that a limestone most likely to be detrimentally expansive is one which contains a significant percentage of dolomite particles (rhombs) enclosed in a matrix of fine-grained calcite (micrite) contaminated with clay material. Since chemical analyses already available on all the approved sources as reported on the "Quarry Log" (5) reflect the presence of dolomite (indicated by $MgCO_3$ contents) and potential clay material (indicated by insoluble residue in HCl), it was decided to use known, reported, log chemistry as a criteria for first-priority sampling and testing. In addition, the specification initially proposed used the minimum values of seven percent $MgCO_3$ and seven percent insolubles combined with excessive expansion of rock cores (greater than 0.3 percent) as a basis for disqualifying ledges. After a sampling and testing program based on those criteria was completed, the Aggregate Control Section began to sample, in their entirety, all sources which contained an expansive ledge. High priority was given to those sources reported by Virginia (Quarry 119 at Jenkins) (3) and the US Corps of Engineers (Quarry 33) (6) as containing material possessing expansive characteristics. The next objective was to complete testing of any source for which samples had been obtained previously, even though non-expansive. Then, as time permitted, sampling of all remaining sources was undertaken. Thus, priority lost significance. Testing on all new or resampled (check-sampled) ledges will be assumed as a regular procedure, and other types of aggregate -- especially gravel -- are to be examined. Currently, experimentation on possible means of reducing expansive characteristics in concrete by dilution with non-expansive aggregate is being conducted.

PROCEDURES

Advice was sought from other states, and agencies, which had experience with such conditions before; and periodicals and publications (1, 2, 3, 4) were examined for information on the subject of alkali-carbonate (de-dolomitization) expansion. Training and practice in the methods of thin-section preparation were obtained at the geology facilities of the University of Kentucky. Training and making the initial sections lasted through February 1973. This was followed by a visit to the Virginia Highway and Transportation Research Council.

During the first months and initial sampling periods, approximately 303 thin sections were prepared and examined; these represented 128 ledges. Hand samples from the ledges were cored, and the remainder of the specimens were exposed on the roof of the laboratory for weathering observations. Some samples of the same material were incorporated into concrete prisms for observations of any significant expansion. The actual laboratory work, then, was a three-part process. Cores and thin sections were made of any chemically suspicious ledge; and, if a degree of expansion persisted in a core (excess of 0.3 percent), concrete beams were made providing the ledge remained accessible for further sampling.

The basic textural characteristic (well-formed dolomite rhombs and dirty, fine-grained calcite matrix) of a potentially expansive ledge were present in over 40 percent of the ledges initially identified. Two thin sections were attempted from each hand sample (one perpendicular and one parallel to the bedding plane). As time and expertise progressed and more sections were studied petrographically under the polarizing microscope, it became evident that the vertical (perpendicular) section was sufficient and reliable for predicting whether a ledge would be expansive or not; and, subsequently, only the vertical section was used in testing.

A petrographic examination of a thin section made with proper machinery (cut-off saws and grinding wheels) in two to three days is, therefore, the most expedient indication of non-expansive nature. Preparation and measurement of cores which are allowed to soak in a NaOH solution may take 56 days. Six months to one year may be necessary to detect or isolate a delayed type of expansion.

The preparation of cores was done initially by the Physical Section of the Materials Laboratory (at that point in time, the Aggregate-Testing Section was not part of the Aggregate Control Section as it now exists). The coring was done in a manner similar to that described in ASTM C 586. Some of the testing procedures in C 586 readily proved to be unnecessary and exceptionally burdensome. Three cores were taken from each ledge, and it became evident soon afterwards that attempts to secure cores mutually perpendicular to each other would be impractical. It was decided that three cores should be consistent with the orientation of the thin sections and be taken vertical to the bedding plane. The initial cores were drilled with a 5/8-inch (15.8-mm), diameter diamond-tipped bit; the ends were polished to a flat surface to facilitate accurate measurement. The cores were approximately 1.25 inch (32 mm) or more in length; and, after being measured individually, they were placed in a 1-normal solution of NaOH for 56 days. They were removed for measurement at 14-day intervals. If any one of the three cores expanded over 0.3 percent of its original length, it was considered to have failed. There were 128 ledges involved at this stage.

The first series of thin-sections and expansion measurements indicated a strong relationship, even though some discrepancies seemed to exist. In this inital study, most of the variation in percentage of expansive material found (31.2 percent) as opposed to that predicted by thin-section (44 percent) can be attributed possibly to two factors: 1) the hand samples which were cored were not always the same samples which were used for making the thin sections and 2) inexperience in preparation and study of thin-sectioning. After the visit to Virginia, accuracy and ability increased both in sample preparation of thin sections and in predictive ability. Nonetheless, a safeguard was employed in the predictions: if a thin section had the slightest indication of having a small area of expansive texture, it was designated as potentially expansive. In addition, through the month of July 1973, two or more geologists petrographically examined each of the thin sections and compared their predictions. If either observer thought a section indicated expansiveness, it was noted as representing an expansive ledge. Also, the examination of the logs and sampling was made more selectively. Ledges formerly combined were again separated whenever possible, and other lithologic changes were notated when present.

After a ledge sample was examined in thin section and an expansive tendency was found in the rock core test, it was brought into the laboratory and crushed into No.-57 size aggregate for inclusion in concrete. Four beam specimens, 3 by 3 by 10 inches (76 by 76 by 254 mm), were prepared for each ledge. Two of these (labeled A and B) were prepared with cement having alkali contents in the range of 0.69 to 0.78 percent, and two (labeled C and D) were prepared with cement having alkalies in the range of 0.48 to 0.53 percent. The concrete was formed in molds having metal studs mounted in each end in such a manner that the specimens could be placed in a comparator and the relative expansion determined. The beams were stored in water at constant temperature and were removed for expansion measurements. Measurements were made at 24 hours (designated original length), 4 weeks, 8 weeks, 16 weeks, 32 weeks, and finally at 64 weeks. One suggested limit for expansion in beams was 0.05 percent (3), and this value was adopted initially as the criterion for failure.

During August 1973, ledgerock samples from the two most highly expansive ledges in the quarry in Simpson county which supplied limestone for the distressed sections of I 65 were obtained for testing in concrete. Each time, new quality (physical) tests of soundness, wear, specific gravity, and absorption and new chemical tests of CaCO , MgCO , insoluble residue, and R O (metal content) were run. An additional thin section was made to insure that the sample from the field at the second sampling was the same ledge originally sampled in the study.

During October 1973, several trends began to emerge. Several ledges judged to have expansive characteristics did not show expansion of the rock core (over 50 percent). Yet, the ability to predict (by absence of expansive texture) non-expansive ledges was almost without exception. One wrong prediction was made; however, this was due to an improperly made thin section. A re-make of the section in question revealed that the ledge should not have been judged as safe. Expansive areas in the section did exist. The result restored confidence in using the petrographic examination for initial screening of all samples to indicate whether or not cores should be tested. Another factor slightly more disturbing was the number of exceptions to the chemical limits (seven percent $MgCO_3$ and seven percent insoluble residue) which were used to initiate the program. More than 40 percent of the ledges studied through September 1973 had a set of chemical values in which one or the other members of the set was less than seven percent. Generally, this was the insoluble residue; and the result was reminding that not only the amount of insoluble residue but the type of residue (clay or quartz) was important.

The laboratory examination and testing of ledge samples could still be described as a three-phase approach:

1) petrographic examination,
2) testing rock cores, and
3) distress observations and expansion measurements of concrete beams.

The problem of expansive aggregate does not seem to be confined to any particular geologic age or formation; although, it does occur more often in Mississippian limestone quarries than Ordovican quarries in Kentucky. Devonian (7, 8, 9, 10) and Silurian deposits do not provide many sources of stone in this state; and, in most cases, the Silurian is relatively free from expansive ledges. A neighboring quarry (No.49, here) in the Devonian and Silurian strata of Indiana does possess the characteristic expansive traits rather uniformly throughout.

On a statewide basis, with over 1,200 ledges having been studied, the estimate is that slightly more than ten percent do possess some degree of expansive character. Over half the ledges studied (approximately 60 percent) are pronounced safe by petrographic screening, and approximately one fourth of the remainder yielded expansive cores. Approximately three-fourths or more of the ledges cored and tested in concrete showed some detrimental character in concrete, whether that be an unusual amount of lineal expansion or significant distress. The program included essentially all accessible ledges in all active quarries supplying Kentucky projects.

PETROGRAPHIC STUDY

The thin sections were made by procedures used by the Division of Research (1, 11, 12), the University of Kentucky Geology Department, and the Virginia Highway and Transportation Research Council (3). A vertical slab was cut with a 24-inch (610-mm), diamond-bladed saw from a hand sample taken as representative of the ledge. This was shaped roughly to a domino-sized chip (3/8 x 3/4 x 1-1/2 inch (9.5 x 19.1 x 38.1 mm)) on a smaller (8-inch (203-mm)) saw. The chip was lapped or hand-rubbed on 240-grit, Handimet paper. The leveled, unscratched surface was then prepared on papers of 320-, 400-, and 600-grit, wet abrasive. The face was polished on soft 600-paper (or dry 600 followed by further buffing on cloth) and mounted on a glass slide with epoxy resin. After the epoxy hardened (usually overnight), the chip was sawed away on an Ingram cut-off saw -- leaving approximately 1/32 inch (0.8 mm). The slide was transferred to the companion Ingram grinder; and the specimen was reduced to approximately 50 microns in thickness. It was reduced by hand to a final thickness of approximately 15 microns with No.-600 grit or a 5-micron grinding compound on a glass plate. The section was stained for calcium carbonate detection with Alizarin Red "S" and sealed with a cover-slip by Canada balsam. After cleaning with acetone and detergent, the section was ready for study. A Zeiss RP 48 (binocular with five objectives) polarizing microscope was used.

The main problems in producing thin sections were failure to make them thin enough at first, trouble with the mounting media (unsuitable batches of epoxy were sometimes used), and equipment breakdowns.

Characteristic expansive texture has been described previously as small, well-formed, dolomite rhombs apparently floating or encased in a fine-grained calcite matrix (micrite) which has been contaminated with clayey, fine particles. It is impossible to see the individual clay particles with a petrographic microscope; however, the general appearance of "dirty" is usually indicated by the fact that the section is uncommonly hard to bring into focus, and the Alizarin Red stain usually looks more brown than red. The dolomite rhombs are distinctive, and the texture should be readily distinguishable.

Due to the volume of material to be examined and the urgency to acquire data relating to expansion, little time was devoted to other characteristics of the rock. Ledges were designated as either SAFE (not possessing suspected texture) or SUSPECT (possessing the suspect texture). Future plans, however, do not limit the use of the tremendous statewide inventory of ledges and thin sections to the study of expansive tendencies. In the event other problems may arise whereby a thin section and a petrographic study of limestones in Kentucky might be needed, such data will be obtained as sources are opened and made as available as the standard physical tests for immediate reference. Equipment for preparing thin-sections cost in excess of $14,000. ASTM C 295 references the equipment for making thin sections.

TESTING CORES IN SOLUTION OF NaOH

Three cores representing a hand sample of a ledge were prepared for measurement by grinding flat, parallel ends. At first, a valve grinder was used; but later cores were faced with thin-section equipment. Initial study cores were taken with a 5/8-inch (15.9-mm) drill bit; however, subsequent cores were taken with a newer apparatus and new bit, 3/8 inch (9.5 mm) in diameter. Measurements were made on 14-day intervals through 56 days: original length (before any soaking), 14 days, 28 days, 42 days, and 56 days. In slight variation from ASTM C 586, all three cores were carried through 56 days instead of 28 days. At that point, the most expansive core was retained, and the other two were discarded. If the retained core expanded more than 0.3 percent, the ledge was flagged to be tested in concrete. The core retained was measured for as much as two years or more at 6-month intervals. This was done primarily to determine how long the cores would continue to expand and to what degree. These observations revealed still another unusual phenomena. Some cores which had shown only minimal expansion or none at all through 56 days began to display amazing growth at 6-month or 1-year intervals. On January 29, 1974, those ledges surpassing 0.5 percent at 6 months, or 1.0 percent in any time period, were included with the other ledges deemed to have expansive character and were also flagged for testing in concrete.

Cores were measured in two ways. Initial cores were measured by hand micrometer on four different opposite points and averaged. Later, a dial micrometer was mounted on an "I beam", and a homemade comparator was used.

CONCRETE BEAMS

This testing followed ASTM C 157 very

closely, except that four beams were used instead of three. This was done to accommodate two beams for each alkali content. Another sideline to the concrete test developed as the result of a minor problem. Storage for beams which had completed the 64-week test period became critical. New ledges were being collected; and, already, two tanks for storage had been procured and filled. It was decided to place the beams with completed measurement on the roof with the hand samples which were already exposed to weathering there. From time to time, the beams were checked and distress observations made. A visual comparison between the hand samples which weathered badly and the concrete beams which expanded or cracked the most indicated a correlation might be drawn. This, indeed, became another way to isolate the most reactive and detrimental ledges of dolomite limestones then being tested.

The first beam measurements completed were taken about May 1974. Some of these beams displayed cracking and indications of expansion to an amazing degree. When a question of labeling arose concerning an expansive beam, it was decided that the beam would be cut on the diamond saw as if it were a hand sample and a thin section of the stone inside made to verify the records. A few other beams were also cut for information, and this resulted in the discovery of "reaction rims" about the more highly expansive, dolomitic limestones.

RESULTS, OBSERVATIONS, AND RECOMMENDATIONS

SUMMARY OF APPROACHES

Accessible ledges in all active quarries approved to furnish aggregate for the Commonwealth of Kentucky have now been examined or are presently under test. This provides an opportunity to reflect on the data and comparison of test results and the various approaches taken.

Initial investigation using chemical criteria from the "Quarry Log" and core measurements in excess of 0.3 percent expansion at 56 days, the basis from which the program started, would have resulted in 62 ledges from 32 quarries being classified as excessively expansive. This would indicate that approximately two ledges per quarry in 32 quarries out of 117 active quarries would necessitate control for use as a concrete aggregate. The alternate approach using the criteria of 0.3 percent core expansion and 0.05 percent concrete beam expansion would have resulted in rejection of 60 ledges from 36 quarries. Forty-six ledges would be common to each set of conditions.

At this point, a new method of finding a practical limit for isolating expansive aggregate was considered. Comparison between already proposed testing procedures (which consisted essentially of charting one set of limits against another to see how many ledges would meet each requirement -- thereby determining their combined statewide impact) seemed to be evading the real problem: What relates to the proven harmful material in the original pavement of I 65-1(13)13? In this light, it definitely seemed more appropriate that, whatever limiting requirements are designated to detect expansive limestone, they must have some direct relationship to the known expansive properties of the material from the problem source. The criteria of 0.6 percent expansion at 56 days in the rock cyclinder test or 0.17 percent expansion in concrete beams at 64 weeks seemed to be the appropriate lower limits to select.

Referring to Figure 1, the value 0.17 is noted as being the lower limit of the lesser of the two most expansive ledges from the problem source (HS-5). From this point upward, there are ten ledges with the same or greater potential for concrete failure as the problem source (HS-4 included). Using these ten ledges for the basis of a comparison of all the characteristics studied in this program produced Table 1. Only two ledges with critical expansion values, 89-9A and 156-8, have a corresponding core expansion of less than 0.6 percent at 56 days. Both of these ledges approach and one significantly exceeds 0.6 percent at 6 months. These ledges show evidence of delayed expansion originally provided for by including ledges with core measurements that pass 0.5 percent at 6 months with the other ledges in the concrete test.

Certainly, it would seem that more ledges studied than the ten top expanding ledges have a dangerous potential for expansion. This is indicated by several ledges having core readings surpassing those of the problem source and having very similar petrographic textures. A 0.6-percent and greater limit for cores also includes these ledges. Knowing that many variables exist in the concrete measurements (the range of alkali cements in high and low beams, the possibility of uneven concentrations of alkali in some sets of beams due to the mixing procedure, and other unforeseen errors), it was also decided to accumulate as much data as possible as it relates to the NaOH core test in a controlled environment.

Observations of the beams also produced a good relationship between the appearance of the beams from the ledges which produced the highest measurements and the hand samples from these same ledges placed on the roof for weathering. Unfortunately, no set of conditions seems to completely relate all the elements of the testing program. A ledge displaying a high expansion in concrete and a disturbing appearance could possess a relatively low core measurement through 56 days; or a ledge could look cracked and disturbing in the hand sample and appearance of the beam and have a high core measurement; yet the actual beam expansion might be relatively low. At least, visual appearance, beam expansion, and core expansion reinforced each other by satisfying the two-out-of-three situation (see Appendix B). Thus, a petrographic examination together with core expansion of 0.6 percent and greater or concrete expansion of 0.17 percent and greater seems the most realistic way to isolate the potentially excessively expansive aggregates. Using this criterion, 47 ledges in 32 quarries are considered to be highly expansive. Several are now being studied regarding the effects of dilution ("sweetening") with non-expansive aggregate in various concentrations.

Each of the expansion tests seems to be uniformly progressive timewise, and an excellent correlation with respect to reducing time may be derived. A 28-day reading in most cases is accurate for predicting 56-day results. In like fashion, 16-week concrete tests reliably indicate the outcome at 64 weeks. Figures 2 and 3 show these relationships. The correlation equations are shown there.

DILUTION-CONTROL EXPERIMENTATION

Several methods of mitigating the alkali-carbonate reaction were available from various research reports prior to this study. Some agencies recommended reducing the alkali content of the cement. The theory is that there is a minimum level of alkalinity (usually given as 0.45 percent or lower) necessary to initiate the reaction. In the case of the alkali-silica reaction, the use of pozzolans is sometimes recommended to minimize the expansion. Seemingly, the only advantage to using cement low in alkali was a reduction of time to expansion. The only cement available with an alkali concentration below 0.45 percent was an aluminate (0.21 percent).

Another method being pursued is the concept of dilution by limiting the percentage of the offending material to be taken from the working face of a quarry -- this is, "selective quarrying". As the first step in establishing the feasibility of dilution, a non-expansive ledge was selected as a standard diluent ("sweetener") to be combined with the most highly expansive ledges discovered in the survey. Two ledges were included in the basic study; 57-2 was used as the diluent. Then, nine ledges of rocks having texture highly expansive and causing expansions in concrete in excess of 0.10 percent were collected along with two moderately expansive ledges and one totally safe ledge.

Some reports (13) indicate that 20 percent expansive material would be admissible if some cracking may be allowed in the concrete. This cracking, of course, would be a telltale sign of continuing unsoundness. A constant cement alkalinity of 0.78 was used in these tests; and, to gain more information on the effects of different concentrations, three percentage combinations (20-80, 30-70, and 50-50) were used. These tests (see Table 2) have progressed through 16 weeks which, before, was the first plateau of a reliable indication of expansion. In prior testing, as previously mentioned, a good correlation between 16 weeks and 64 weeks existed. Using this correlation equation, the dilution figures indicate that 18 of the beams made with 57-2 as a common diluent will exceed the 0.05 limit suggested in Virginia's study (3). The 20-80 and 30-70 dilution beams averaged much lower expansion than the 50-50 beams. There are several indications that the 50-percent cut would be unsatisfactory and much more unpredictable than the lower concentrations. Thus 30 percent and under, or most likely 20 percent, seems to be the level offering the more favorable evidence for dilution. It may be that any allowances for dilution would be counter-productive insofar as the welfare of concrete structures may be involved.

The Division of Materials plans to continue this line of investigation with several different methods of producing various concentrations. Test beams will be made of finished product samples from the sources possessing a high or borderline concentration of expansive material in the quarry face. Another method of examination will relate to laboratory-prepared finished products which will more precisely reflect the percentage by footage of the working face.

SCANNING ELECTRON MICROGRAPHS

Several samples were subjected to scanning electron microscope (SEM) examination (see Appendix C). These were three highly expansive samples (HS-4, HS-5, and 116-11); one sample possessing petrographically suspect texture but which did not expand in NaOH (14-15T); and one highly dolomitic which was the standard, non-expansive control used in the concrete beam tests.

The individual samples were examined in two ways. Cores were drilled from the hand samples and broken horizontally to fit the small circular plates for the SEM. This provided fresh material that had not been soaked in NaOH. Cores which had completed the NaOH test were also used as a comparison. Some of these cores from the HS quarry had been prepared (mounted on petrographic slides) to observe evidences of expansion; that is, cracks under the polarizing microscope. Some of these cracks developed as early as when the 14- and 28-day measurements were taken. The cracking was transverse, oblique, and in some cases parallel to the bedding plane of the sample; and these areas were examined extensively. The SEM is located at the University of Kentucky.

Only the flaky, thinly laminated, sometimes disoriented patterns and microtextures were associated with severe expansion. It seems likely that clayey impurities present at the time of co-deposition or precipitation have interferred with recrystallization processes (metamorphism).

SUMMARY

It is easy to visualize many problems inherent in the concept of using dilution as a control. Duplication of results will be more difficult to obtain because variances within ledges will be more likely to emerge; the time element also influences this test with respect to repeatability; a ledge is not always available for immediate resampling due to blasting procedures and geological phenomena (faulting etc.); and there are greater possibilities that the same finished product may never be available for resampling. Whether this process will be practical in border-line conditions is questionable; however, present experimentation does indicate it may offer some alternative to selective quarrying -- at least, when the percentages are small.

Having a reliable means to relate the potential expansion of any ledge tested to the ledges which initiated the problem, the impact of implementing some form of contol should be considered. Each source which contains an expansive lithology should be restricted in the production of crushed stone for concrete aggregate. Selective quarrying -- that is, excluding the expansive ledge -- is the most effective. In some cases, the less effective but possibly more economical method of dilution -- that is, allowing a small percentage of expansive material with a greater percentage of non-expansive material -- might be acceptable if it is determined from experimentation that a practical limit exists. Dilution methods are easily conceived but are difficult to regulate and enforce in quarrying.

To better understand the details of quarry operation, Appendix D (quarry profiles) is offered.

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The sampling and testing was done largely by Mr. Coy under David L. Arnall, Chief Geologist, Division of Materials. Concrete specimens were made under the supervision of James D. Stone.

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The scanning electron micrographs were made by Henry Southgate, Agricultural Experiment Station, University of Kentucky.

Interest and patience in upper echelons and elsewhere and among several colleagues is appreciated.

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TABLE 1. SUMMARY OF CHARACTERISTICS OF TEN POTENTIALLY TROUBLESOME LEDGES

QUARRY-LEDGE	PERCENT EXPANSION: CORES 28 DAYS	CORES 56 DAYS	CORES 180 DAYS	BEAMS 16 WEEKS	BEAMS 64 WEEKS	VISUAL CONDITION OF SPECIMENS: BEAMS	HAND SPECIMENS	PERCENT ALKALI (BY WEIGHT) IN THE CEMENT	CHEMICAL COMPOSITION (PERCENT BY WEIGHT): CACO3	MGCO3	INSOLUBLES	LEDGE THICKNESS (FEET)
HS-4	0.63	0.81		0.100	0.201	VERY BAD	BADLY CRACKED	0.69	74.9	14.9	9.2	3
	0.73	0.99		0.099	0.309							
	0.58	0.86		0.068	0.167			0.48				
	0.68	0.92		0.056	0.129							
HS-5	2.27	3.42		0.070	0.178	VERY BAD	BADLY CRACKED	0.69	73.5	16.4	9.3	5
	2.27	3.33		0.057	0.144							
	2.29	3.31		0.039	0.084			0.48				
	2.36	3.53		0.041	0.096							
2-6	0.23	0.39		0.097	0.166	VERY BAD	GOOD	0.69	74.7	13.0	9.8	14 - 16
	0.36	0.52		0.110	0.248							
	0.82	1.35	1.83	BROKE				0.48				
				0.056	0.167							
14-12T	0.05	0.13		0.128	0.288	VERY BAD	DISINTEGRATED	0.69	77.7	11.1	11.0	2 - 3
	4.58	4.22	6.07	0.106	0.234							
	BROKE			0.049	0.101			0.48				
				0.041	0.103							
20-12B	0.78	0.91	0.97	0.166	0.292	VERY BAD	NO SPECIMEN	0.69	76.3	17.4	5.1	4 - 5
	0.74	0.87		0.155	0.259							
	0.62	0.83		0.048	0.115			0.48				
				0.045	0.098							
23-3	1.19	1.94	2.38	0.146	0.235	VERY BAD	CRACKED	0.78	77.9	10.4	11.4	3
	1.18	1.85		0.131	0.227							
	1.16	1.90		0.078	0.081			0.53				
				0.044	0.080							
89-9A	0.20	0.31		0.133	0.249	VERY BAD	NO SPECIMEN	0.69	74.5	19.5	7.1	5
	0.44	0.57	0.67	0.110	0.219							
	0.36	0.45		0.062	0.122			0.48				
				0.056	0.103							
89-10	1.51	1.79		0.126	0.227	VERY BAD	NO SPECIMEN	0.69	70.0	24.4	8.0	3
	1.56	1.74		0.127	0.239							
	3.03	3.22	3.44	0.067	0.120			0.48				
				0.057	0.114							
116-11	1.24	1.47	1.85	0.180	0.320	VERY BAD	DISINTEGRATED	0.78	72.3	13.3	12.2	10 - 12
	0.43	1.12		0.168	0.300							
	0.66	1.16		0.169	0.162			0.53				
				0.062	0.153							
156-8	0.25	0.27	0.55	0.134	0.262	VERY BAD	NO SPECIMEN	0.69	71.6	13.9	13.1	1 - 3
	0.22	0.24		0.135	0.270							
	0.24	0.25		0.050	0.095			0.48				
				0.053	0.098							

TABLE 2. SUMMARY OF DILUTION-CONTROL TESTS

QUARRY-LEDGE	CONCENTRATION*	SPECIMEN	PERCENT EXPANSION OF BEAMS 4 WEEKS	8 WEEKS	16 WEEKS
SUSPECT AGGREGATES					
16-1A	100 - 0	A	0.041	0.069	0.098
		B	0.037	0.064	0.094
	50 - 50	A	0.022	0.034	0.036
		B	0.023	0.035	0.035
	30 - 70	A	0.022	0.022	0.027
		B	0.024	0.024	0.033
	20 - 80	A	0.013	0.019	0.021
		B	0.013	0.020	0.023
20-12B	100 - 0	A	0.075	0.120	0.166
		B	0.072	0.112	0.155
	50 - 50	A	0.013	0.013	0.018
		B	0.015	0.015	0.016
	30 - 70	A	0.003	0.008	0.011
		B	0.008	0.013	0.013
	20 - 80	A	0.011	0.017	0.017
		B	0.018	0.020	0.023
22E-4	100 - 0	A	0.045	0.037	0.062
		B	0.040	0.042	0.062
	50 - 50	A	0.013	0.015	0.022
		B	0.019	0.021	0.028
	30 - 70	A	0.018	0.026	0.028
		B	0.018	0.024	0.028
	20 - 80	A	0.015	0.020	0.021
		B	0.014	0.020	0.022
23-3	100 - 0	A	0.045	0.083	0.146
		B	0.032	0.072	0.131
	50 - 50	A	0.015	0.020	0.020
		B	0.016	0.022	0.027
	30 - 70	A	0.008	0.012	0.018
		B	0.009	0.010	0.015
	20 - 80	A	0.011	0.014	0.017
		B	0.013	0.016	0.020
71-3	100 - 0	A	0.017	0.016	0.128
		B	0.032	0.023	0.025
	50 - 50	A	0.012	0.012	0.016
		B	0.014	0.013	0.016
	30 - 70	A	0.005	0.011	0.010
		B	0.003	0.009	0.008
	20 - 80	A	0.003	0.010	0.012
		B	0.002	0.009	0.011

TABLE 2. (CON'T)

QUARRY-LEDGE	CONCEN-TRATION*	SPECI-MEN	PERCENT EXPANSION OF BEAMS 4 WEEKS	8 WEEKS	16 WEEKS
SUSPECT AGGREGATES					
87-12	50 - 50	A	0.012	0.010	0.020
		B	0.014	0.013	0.015
	30 - 70	A	0.022	0.028	0.028
		B	0.007	0.010	0.010
	20 - 80	A	0.009	0.013	0.015
		B	0.010	0.015	0.016
87-12A	100 - 0	A	0.037	0.054	0.060
		B	0.020	0.036	0.044
	50 - 50	A	0.008	0.005	0.009
		B	0.005	0.006	0.011
	30 - 70	A	0.005	0.016	0.016
		B	0.011	0.015	0.015
	20 - 80	A	0.010	0.011	0.014
		B	0.009	0.017	0.017
89-9B	100 - 0	A	0.023	0.020	0.050
		B	0.021	0.020	0.046
	50 - 50	A	0.002	0.002	0.006
		B	0.010	0.011	0.015
	30 - 70	A	0.004	0.009	0.009
		B	0.008	0.014	0.015
	20 - 80	A	0.005	0.012	0.014
		B	0.006	0.010	0.011
89-10	100 - 0	A	0.064	0.081	0.126
		B	0.057	0.082	0.127
	50 - 50	A	0.012	0.012	0.015
		B	0.012	0.011	0.015
	30 - 70	A	0.013	0.020	0.020
		B	0.014	0.021	0.020
	20 - 80	A	0.003	0.009	0.009
88-11	100 - 0	A	0.014	0.028	0.026
		B	0.012	0.032	0.038
	50 - 50	A	0.002	0.003	0.009
		B	0.006	0.006	0.007
	30 - 70	A	0.006	0.013	0.011
		B	0.006	0.003	0.008
	20 - 80	A	0.006	0.012	0.012
		B	0.008	0.013	0.013

TABLE 2. (CON'T)

QUARRY-LEDGE	CONCEN-TRATION*	SPECI-MEN	PERCENT EXPANSION OF BEAMS 4 WEEKS	8 WEEKS	16 WEEKS
SUSPECT AGGREGATES					
95-4/5	100 - 0	A	0.015	0.020	0.035
		B	0.014	0.147	0.154
	50 - 50	A	0.023	0.024	0.029
		B	0.025	0.026	0.032
	30 - 70	A	0.019	0.026	0.026
		B	0.012	0.028	0.029
	20 - 80	A	0.003	0.009	0.011
		B	0.005	0.011	0.012
116-11	100 - 0	A	0.049	0.100	0.180
		B	0.046	0.095	0.168
	50 - 50	A	0.032	0.040	0.047
		B	0.026	0.030	0.035
	30 - 70	A	0.020	0.026	0.027
		B	0.020	0.030	0.030
	20 - 80	A	0.018	0.021	0.022
		B	0.015	0.014	0.016
NON-EXPANSIVE REFERENCE AGGREGATES					
59-4	100 - 0	A	-0.003	0.016	0.020
		B	0.007	0.004	0.005

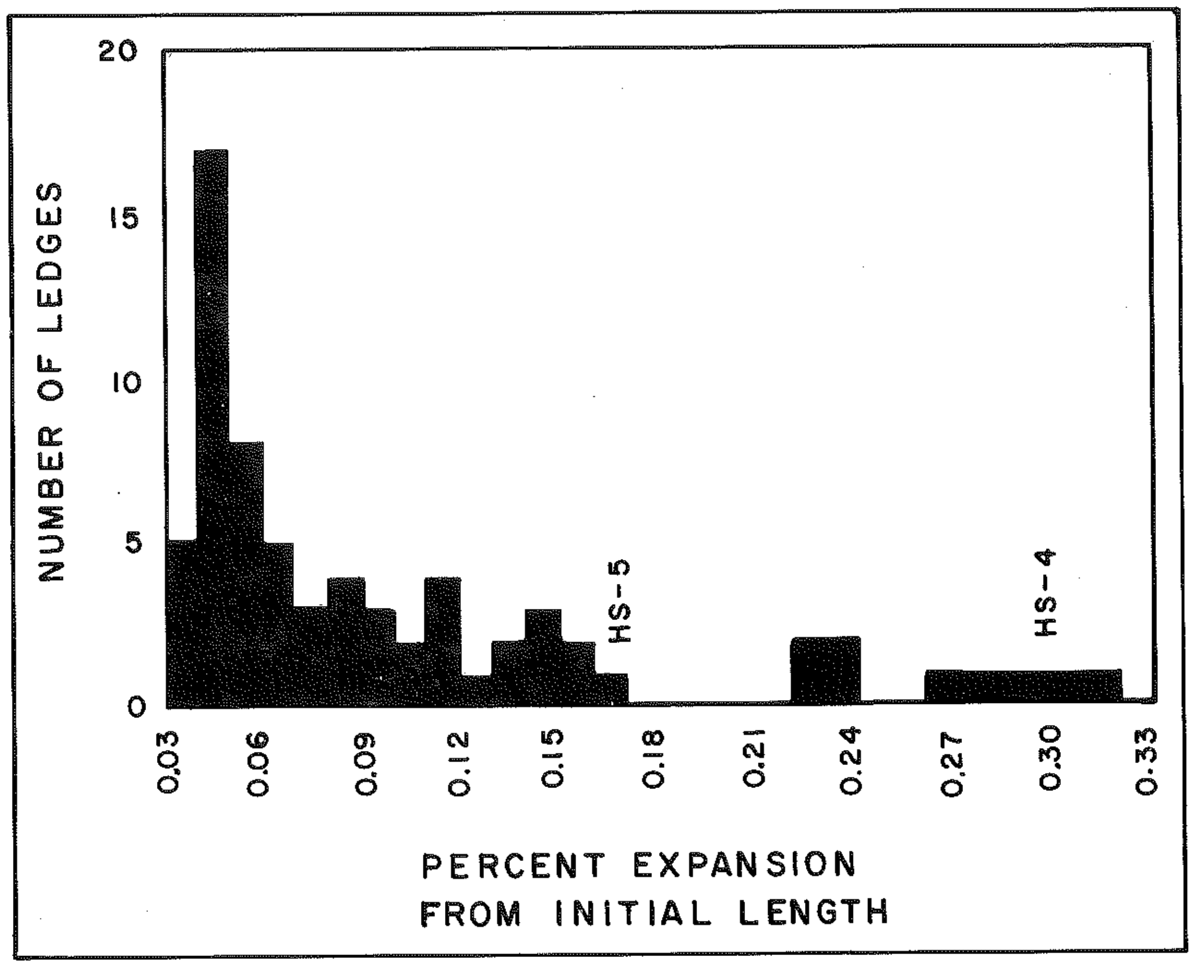


Figure 1. Expansion of Concrete Beams after 64 Weeks.

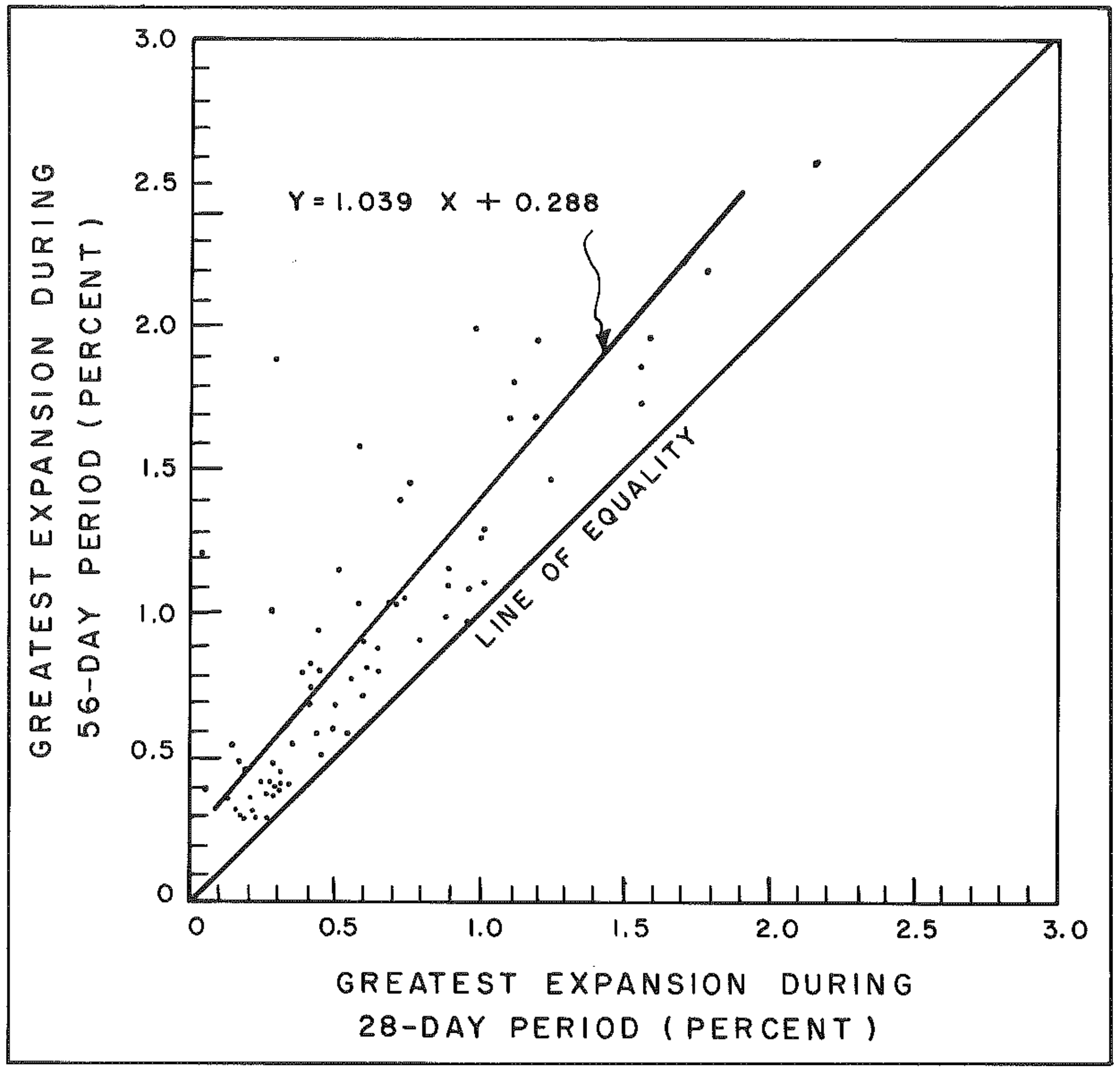


Figure 2. Correlation of 56- and 28-day Expansion of Cores.

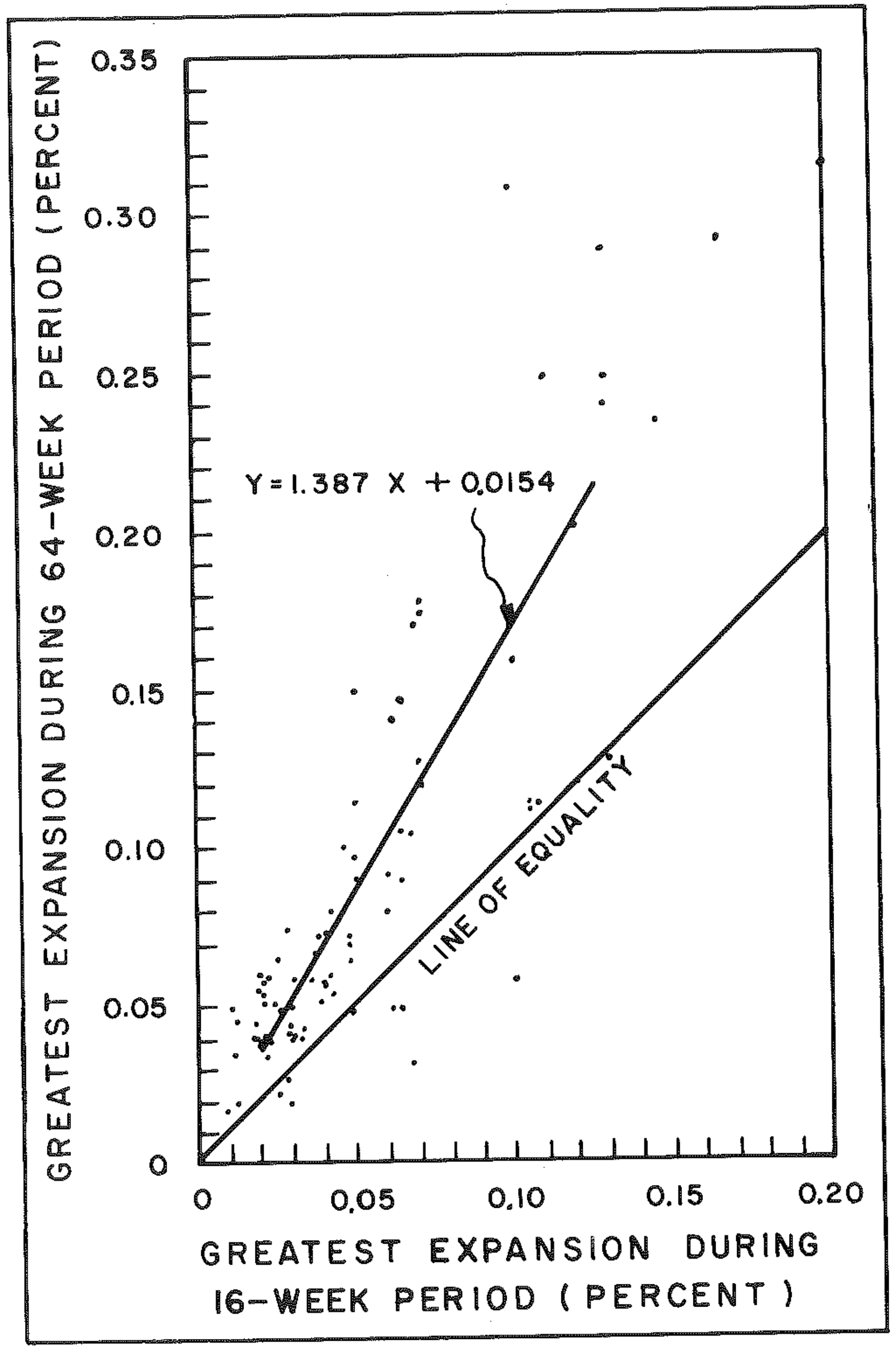
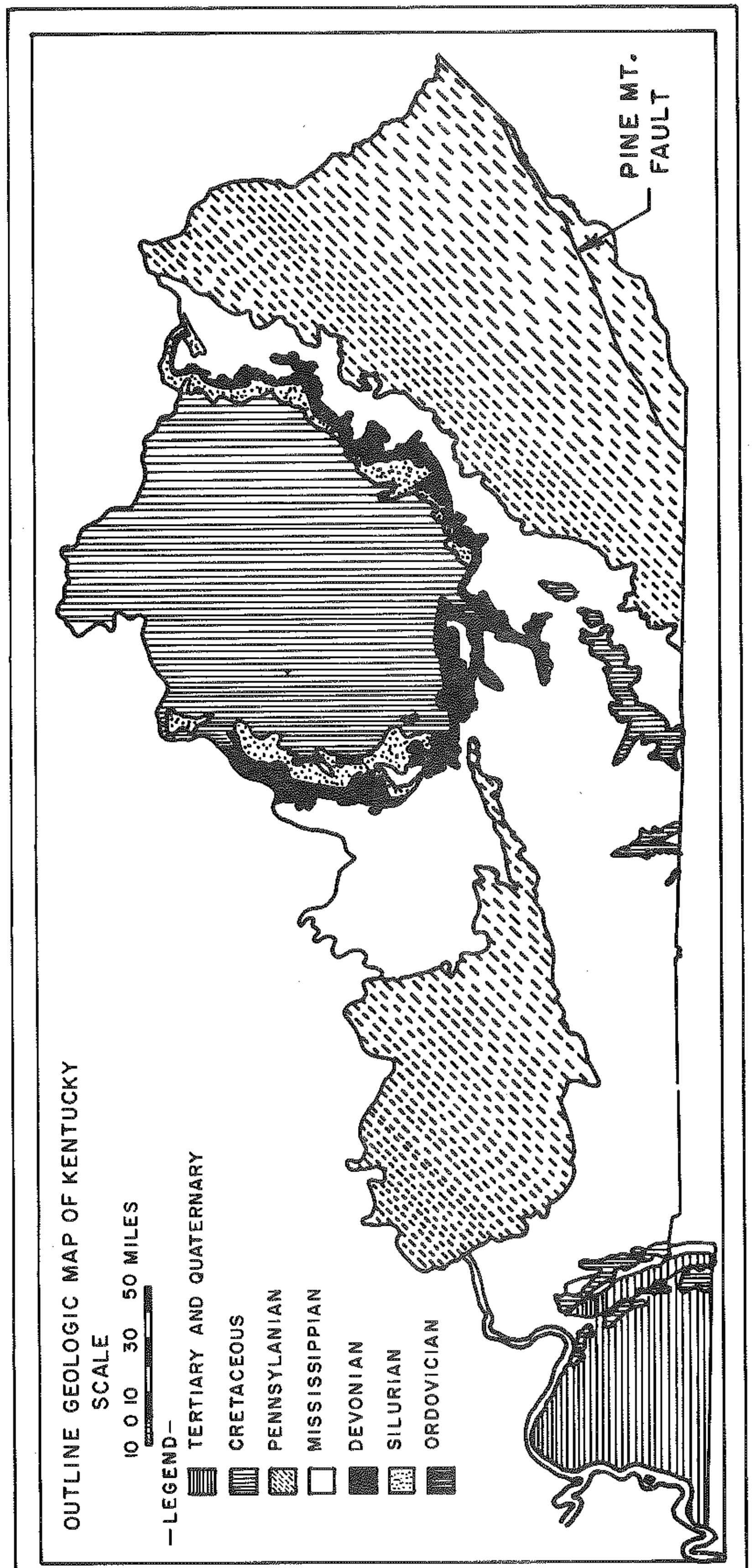


Figure 3. Correlation of 16- and 64-week Expansion of Concrete Beams.

(Pages 18 through 32 purposely omitted)

APPENDIX A

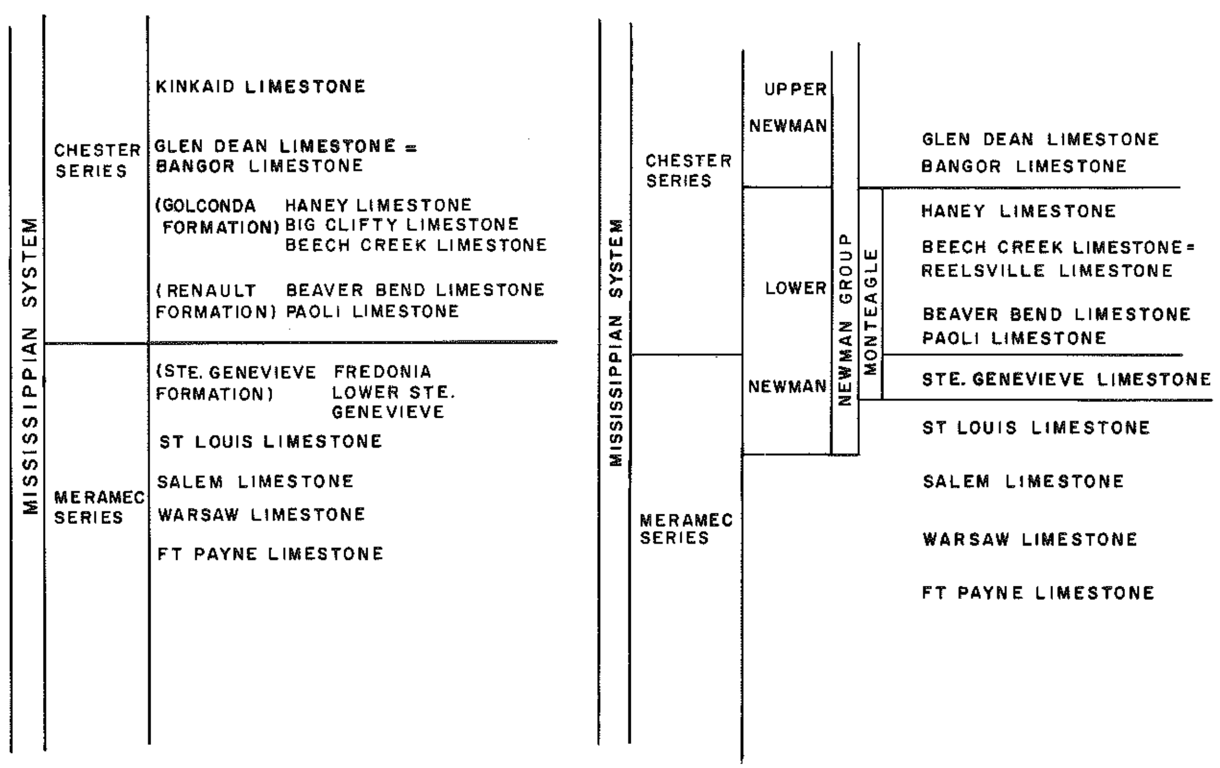
GEOLOGY OF KENTUCKY


OUTLINE GEOLOGIC MAP OF KENTUCKY
SCALE
10 0 10 30 50 MILES
—LEGEND—
TERTIARY AND QUATERNARY
CRETACEOUS
PENNSYLANIAN
MISSISSIPPIAN
DEVONIAN
SILURIAN
ORDOVICIAN
PINE MT. FAULT

MISSISSIPPIAN FORMATIONS SUPPLY MANY SOURSES OF LIMESTONE IN WESTERN AND EASTERN KENTUCKY; GENERAL STRATIGRAPHIC COLUMNS FOR THESE AREAS ARE SHOWN BELOW

GENERAL COLUMNAR SECTION FOR WESTERN KENTUCKY

GENERAL COLUMNAR SECTION FOR EASTERN KENTUCKY



APPENDIX B

COMPARISONS OF CONCRETE BEAMS AND HAND SPECIMENS

APPENDIX B

COMPARISONS OF CONCRETE BEAMS AND HAND SAMPLES OF RESEARCH LEDGES

Visual examinations of concrete beams and hand samples which had been weathering atop the Division of Materials laboratory were made. Descriptions used are the opinions of two and in some instances three observers regarding the condition of the stone and concrete. Only a general, overall comparison based upon the appearnace of surface features was attempted. No sample was manually broken open or disturbed with any tool. The observers were D. Newton, D. Kincaid, and R. Coy.

RATING SCALES

Rating Scale for Concrete Beams: (Samples viewed 3-11-77)	Very Poor (Bad) Poor (Bad) Fair Good Very Good
Rating Scale for Hand Samples: (Samples viewed 9-26-76)	Disintegrated Cracked Fair Good Very Good

SUMMARY OF VISUAL COMPARISONS

CONCRETE BEAMS	HAND SAMPLES
Very Poor	Disintegrated
Poor	Cracked
Fair	Fair
Good	Good
Very Good	Very Good

Very Poor-Disintegrated 14-12T 116-11	Very Poor-Cracked HS-4 HS-5 (23-3) (49-9)	Very Poor-Fair 2-4	Very Poor-Good 2-6 7-7 9-8 15-1 (15-2) (22W-8) 85-1 120-14	Very Poor-Very Good 14-5T
Poor-Disintegrated 92-2TD	Poor-Cracked 2-1 14-11T 49-12	Poor-Fair 2-3	Poor-Good (15-2) 20-10 (47-23) 49-8 120-1/3	Poor-Very Good
Fair-Disintegrated	Fair-Cracked 33-4 (49-9) 119-8	Fair-Fair	Fair-Good 111-1 119-2 88-1 (95-45) (22W-5) 27-5 35-7 (47-23) (49-8) 85-2 85-3	Fair-Very Good
Good-Disintegrated 116-12	Good-Cracked 13-3	Good Fair	Good-Good 9-5 (22W-5) (49-8) 1-4/5 122-2	Good-Very Good
Very Good-Disintegrated	Very Good-Cracked	Very Good-Fair	Very Good-Good (22W-8)	Very Good-Very Good

Very Poor-Disintegrated	2	3.9%	30.5%
Very Poor-Cracked	5	9.8%	
Very Poor-Fair	1	2.0%	
Very Poor-Good	8	14.8%	
Very Poor-Very Good	1	2.0%	
Poor-Disintegrated	1	2.0%	
Poor-Cracked	3	5.9%	
Poor-Fair	1	2.0%	
Poor-Good	5	9.8%	
Fair-Cracked	3	5.9%	
Fair-Good	13	25.5%	25.5%
Good-Disintegrated	1	2.0%	
Good-Cracked	1	2.0%	
Good-Good	5	9.8%	
Very Good-Good	1	2.0%	
Poor-Very Good Fair-Disintegrated Fair-Fair Fair-Very Good Good-Fair Very Good-Very Good	0		
	51		

SUMMARY OF DATA AND OBSERVATIONS

QUARRY-LEDGE	CONCRETE BEAMS CONDITION	CONCRETE BEAMS PERCENT MAXIMUM EXPANSION	CONDITION OF HAND SPECIMEN	PERCENT MAXIMUM EXPANSION OF CORES AT 56 DAYS	PER-CENT CACO3	PER-CENT MGCO3	PERCENT INSOLUBLE
HS-4	VERY POOR	0.309		0.99**	74.9	14.9	9.2***
HS-5	VERY POOR	0.178	BADLY CRACKED	3.53**	73.5	16.4	9.3***
2-1	POOR	0.064	CRACKED	1.87**	97.9	2.7	1.0
2-3	POOR	0.114	FAIR	1.68**	94.4	2.2	1.6
2-4	VERY POOR	0.121	FAIR	1.74**	50.6	21.7	22.6***
2-6	VERY POOR	0.248	GOOD	1.35**	74.7	13.0	9.8***
2-7			GOOD	0.12			
2-8		0.009		0.38*	68.6	22.6	9.9***
2-11	POOR	0.128		0.80**	69.2	21.3	9.5***
3-3	GOOD	0.035		0.48*	69.2	9.4	20.5***
7-1A	GOOD	0.042		3.11**	68.4	11.8	16.5***
7-2C	POOR	0.170		1.29**	69.9	20.3	6.9
7-6			GOOD				
7-7	VERY POOR	0.040	GOOD	0.30			
9-5	GOOD	0.015	GOOD	0.02			
9-7	VERY POOR	0.174		0.91**	90.6	5.2	3.9
9-8	VERY POOR	0.114	GOOD	1.99**	79.8	8.7	8.8***
11-5T			GOOD	0.07			
11-6T		0.020	GOOD	0.83**	46.9	29.4	18.1***
11-9T		0.090		0.94**	80.9	8.6	11.0***
12-8B	POOR	0.092		1.06**	79.9	15.9	4.5
13-2			CRACKED	0.14			
13-3	GOOD	0.068	CRACKED	0.68**	63.8	18.4	13.3***
13-4	VERY POOR	0.143		0.20			
14-5T	VERY POOR	0.035	VERY GOOD	0.31*	77.2	15.0	7.4***
14-11T	POOR	0.104	CRACKED	1.46**	70.8	14.6	12.2***
14-12T	VERY POOR	0.288	DISINTEGRATED	4.22**	77.7	11.1	11.0***
14-17T		0.075		0.29	75.3	6.4	13.3
14-29T	FAIR	0.052		0.41*	80.2	16.5	4.8
15-1	VERY POOR	0.046	GOOD	0.78**	68.9	11.2	16.2***
15-2	VERY POOR	0.090	GOOD	1.16**	66.8	11.8	21.6***
16-1A	VERY POOR	0.158		0.77**	78.0	16.9	5.6
20-10	POOR	0.081	GOOD	0.39*	69.1	23.0	7.7***
20-12B	VERY POOR	0.292		0.91**	76.3	17.4	5.1
22E-4	GOOD	0.136		2.56**	64.7	25.1	8.8***
22W-5	FAIR	0.055	GOOD	0.78**	74.8	17.7	7.4***
22W-6			GOOD	0.08			
22W-8	VERY POOR	0.051	GOOD	0.30	62.3	27.8	7.8***
23-2T	VERY GOOD	0.067		0.51*	83.8	10.7	4.3
23-3	VERY POOR	0.235	CRACKED	1.94**	77.9	10.4	11.4***
23-5	VERY GOOD	0.058		1.04**	91.1	5.8	2.9
26-4A	GOOD	0.039		1.11**	85.3	9.7	5.0
26-4B	GOOD	0.047		0.64**			
27-4				0.33*			
27-5	FAIR	0.045	GOOD	0.36*	64.1	27.3	8.0***

SUMMARY OF DATA AND OBSERVATIONS

QUARRY-LEDGE	CONCRETE BEAMS CONDITION	PERCENT MAXIMUM EXPANSION	CONDITION OF HAND SPECIMEN	PERCENT MAXIMUM EXPANSION OF CORES AT 56 DAYS	PER-CENT CACO3	PER-CENT MGCO3	PERCENT INSOLUBLE
29-2			GOOD	0.09			
30-2T				3.01**	60.4	22.1	15.3***
32-3			GOOD	0.19			
32-4			CRACKED	0.06			
33-4	FAIR	0.061	CRACKED	0.25			
33-5	FAIR	0.097		0.45*	62.6	22.1	12.6***
35-1			GOOD	0.10			
35-6	FAIR	0.100	GOOD	0.41*	75.4	13.5	10.6***
35-7	FAIR	0.061	GOOD	0.33*	69.3	17.0	11.3***
35-8	POOR	0.126		1.85**	57.7	22.1	17.9***
36-4			GOOD	0.06			
36-6				1.73**	89.6	2.4	8.6
37-2			GOOD	0.01			
37-5			GOOD	0.11			
38-1			GOOD	0.10			
38-2			GOOD	0.04			
38-4B				0.46*	70.1	14.3	14.5***
38-4T				1.10**	84.1	10.9	5.4
44-1A			GOOD	0.13			
46-2			GOOD	0.08			
47-17			GOOD				
47-19			GOOD				
47-23	FAIR	0.106	GOOD	0.98**	74.3	18.9	9.0***
49-6			GOOD	0.05			
49-7		0.043		0.30	81.2	8.5	9.4***
49-8	POOR	0.080	GOOD	0.38*	73.9	10.7	13.8***
49-9	POOR	0.055	CRACKED	0.72**	58.9	19.9	18.8***
49-10	POOR	0.075	GOOD	0.42*	78.9	8.6	10.5***
49-11			GOOD	0.44			
49-12	POOR	0.072	CRACKED	0.48*	81.3	10.0	9.6***
50-1			GOOD	0.03			
50-2			GOOD	0.06			
50-3			GOOD	0.05			
51-3B		0.043		0.68**	89.9	8.2	3.4
52-2T			GOOD	0.08			
54-1			GOOD	0.03			
54-2			GOOD	0.05			
56-4		0.051		0.57*	83.8	12.6	4.6
56-5			GOOD	0.11			
56-7			GOOD	0.18			
57-1			GOOD	0.09			
57-2	GOOD	0.029		0.06			
57-4			GOOD	0.02			
58-1A			CRACKED	0.08			
58-1B			GOOD	0.08			
58-5			GOOD	0.05			
59-4	FAIR	0.035	GOOD	0.05			
61-1A			GOOD	0.10			
61-3			GOOD	0.10			
61-4			CRACKED	0.19			

SUMMARY OF DATA AND OBSERVATIONS

QUARRY-LEDGE	CONCRETE BEAMS: CONDITION	CONCRETE BEAMS: PERCENT MAXIMUM EXPANSION	CONDITION OF HAND SPECIMEN	PERCENT MAXIMUM EXPANSION OF CORES AT 56 DAYS	PER-CENT CACO3	PER-CENT MGCO3	PERCENT INSOLUBLE
69-7				1.14**	77.4	6.9	14.2
70-5		0.029			80.7	12.8	7.7***
70-6			GOOD	0.16			
71-3		0.128		0.88**	63.1	36.3	4.5
73-3			GOOD	0.03			
73-14		0.038		0.31*	85.9	9.9	5.3
75-4			DISINTEGRATED				
82-3			GOOD	0.08			
85-1	VERY POOR	0.061	GOOD	0.79**	67.2	15.3	17.8***
85-2	FAIR	0.073	GOOD	0.33*	74.3	10.5	14.1***
85-3	FAIR	0.049	GOOD	0.42*	66.9	10.0	18.8***
85-4	GOOD	0.039		0.36*	64.3	8.8	21.4***
85-5	FAIR	0.031		0.09			
86-3	VERY POOR	0.057		1.16**	61.4	21.6	13.6***
86-6/7			GOOD	0.11			
87-2T		0.018		0.80**	88.0	3.8	9.2
87-11			GOOD	0.04			
87-12		0.148		1.21**	54.9	28.6	16.5***
88-1		0.041	GOOD	0.32*			
88-2			GOOD	0.07			
88-11	FAIR	0.061		1.03**	79.4	16.4	7.5***
88-12	VERY POOR	0.150		4.90**	65.3	20.4	12.2***
89-9A	VERY POOR	0.249		0.57*	74.5	19.5	7.1***
89-9B	GOOD	0.070		1.08**	85.9	8.9	6.7
89-10	VERY POOR	0.239		3.22**	70.0	24.4	8.0***
89-13		0.050		0.54*	86.0	14.5	3.0
94-2T		0.045		2.18**	51.6	30.1	15.1***
95-4/5	FAIR	0.154	GOOD	0.74**	73.2	16.2	7.9***
96/1-4/5	GOOD	0.044	GOOD	1.96**	73.2	15.2	10.3***
106-6		0.066		5.18**	79.7	8.3	9.7***
111-1	FAIR	0.055	GOOD	0.47*	73.9	10.1	13.6***
112-8			GOOD				
112-12/14			GOOD				
114-7	VERY GOOD	0.043		0.39*	88.4	6.3	5.7
116-4			DISINTEGRATED				
116-11	VERY POOR	0.320	DISINTEGRATED	1.47**	72.3	13.3	12.2***
116-12	GOOD	0.037	DISINTEGRATED	1.02**	51.6	32.5	12.7***
116-13			DISINTEGRATED	0.47*			
117-2			GOOD	0.17			
119-2	FAIR	0.053	GOOD	0.39*	44.0	25.3	26.5***
119-8	FAIR	0.056	CRACKED	0.54*	75.2	12.5	11.3***
119-9			GOOD	-0.08			
119-14			CRACKED	0.14			
119-15			CRACKED	0.19			
119-16			CRACKED	-0.09			
119-21	VERY POOR	0.041		1.51**	63.6	8.3	23.7***
120-1/3	POOR	0.034	GOOD	0.29	63.4	8.5	25.3***
120-4			GOOD				
120-12			GOOD				
120-14	VERY POOR	0.059	GOOD	1.40**	81.3	9.2	8.8***

SUMMARY OF DATA AND OBSERVATIONS

QUARRY-LEDGE	CONCRETE BEAMS CONDITION	CONCRETE BEAMS PERCENT MAXIMUM EXPANSION	CONDITION OF HAND SPECIMEN	PERCENT MAXIMUM EXPANSION OF CORES AT 56 DAYS	PER-CENT CACO3	PER-CENT MGCO3	PERCENT INSOLUBLE
121-1			GOOD	0.02			
121-7			GOOD	0.11			
122-2	GOOD	0.025	GOOD	0.11			
122-6			GOOD	0.00			
122-11	GOOD	0.054		0.46*	71.7	20.3	8.0***
122-13	VERY POOR	0.064		1.68**	73.2	7.4	16.7***
123-13				0.33*	74.9	9.2	19.3***
123-18			GOOD				
127-1			GOOD	0.00			
143-20			CRACKED				
144-2B			GOOD	0.59*	48.2	25.0	17.6***
148-4	FAIR	0.042		1.62**	72.4	14.7	11.9***
148-8			GOOD	1.62**			
156-8	VERY POOR	0.270		2.70**			

* EXCEEDS 0.3 PERCENT EXPANSION OF CORES IN 56 DAYS
** EXCEEDS 0.6 PERCENT EXPANSION OF CORES IN 56 DAYS
*** SPECIMEN IDENTIFIED BY CRITERION (>7 PERCENT MGCO3 AND >7 PERCENT INSOLUBLES) AS BEING EXPANSIVE

APPENDIX C

PHOTOMICROGRAPHS

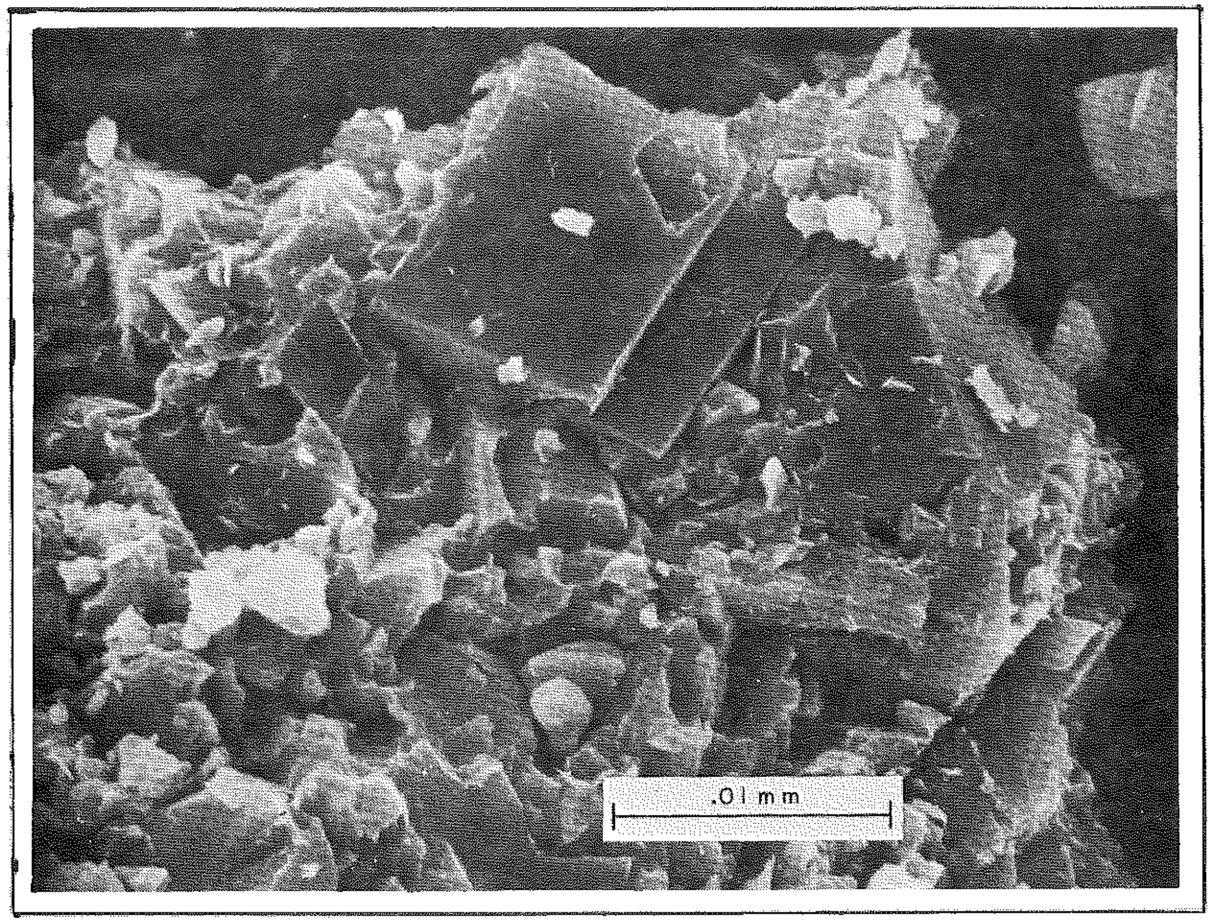


Figure C-1. Expansive Limestone (H5-4); Fractured Surface. Platyness indicates weakness along cleavage planes.

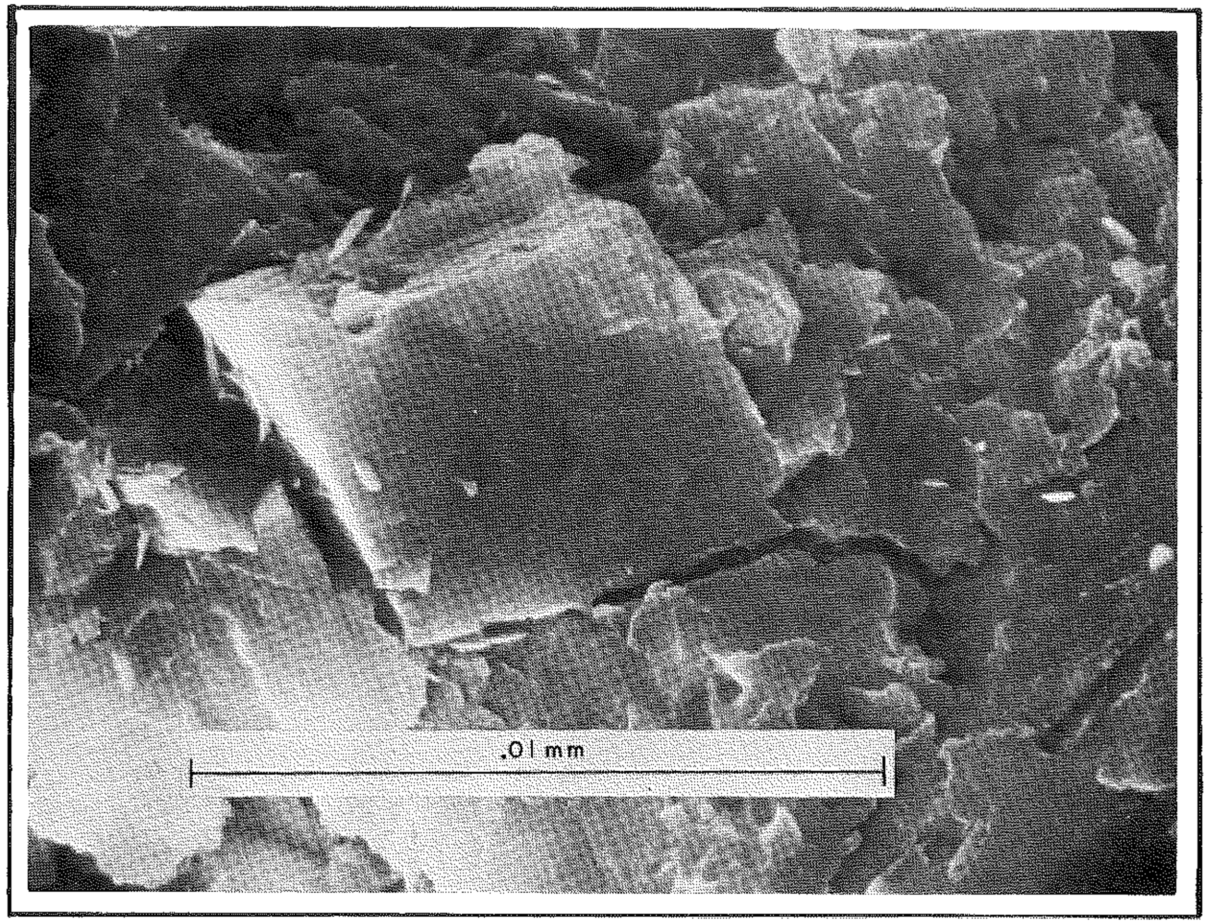


Figure C-2. Expansive Limestone (H5-4); Fractured Surface. Platyness is more apparent than in Figure C-1.

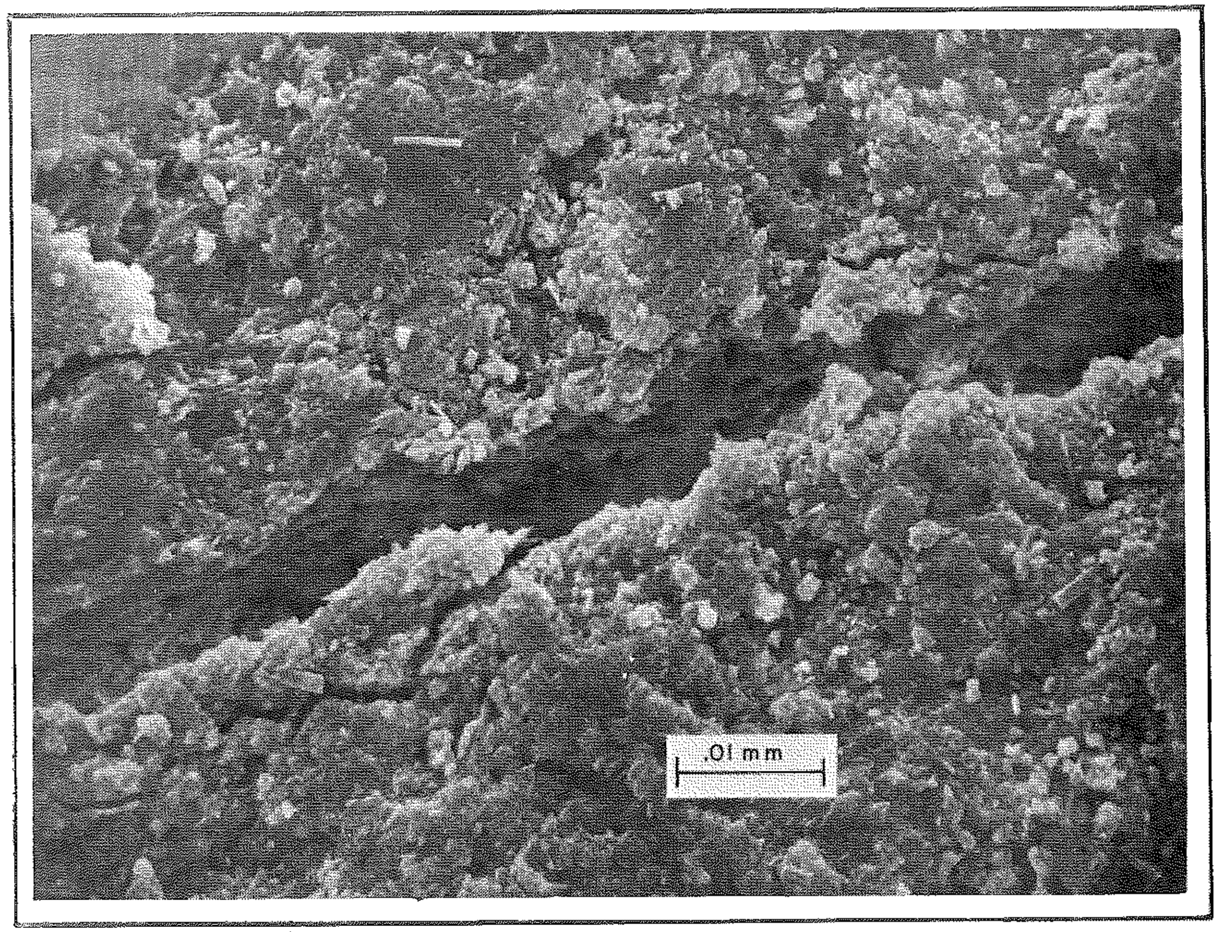


Figure C-3. Highly Expansive Limestone (H5-5); Shows Platyness, Flakiness, and Disorder. Crack occurred naturally.

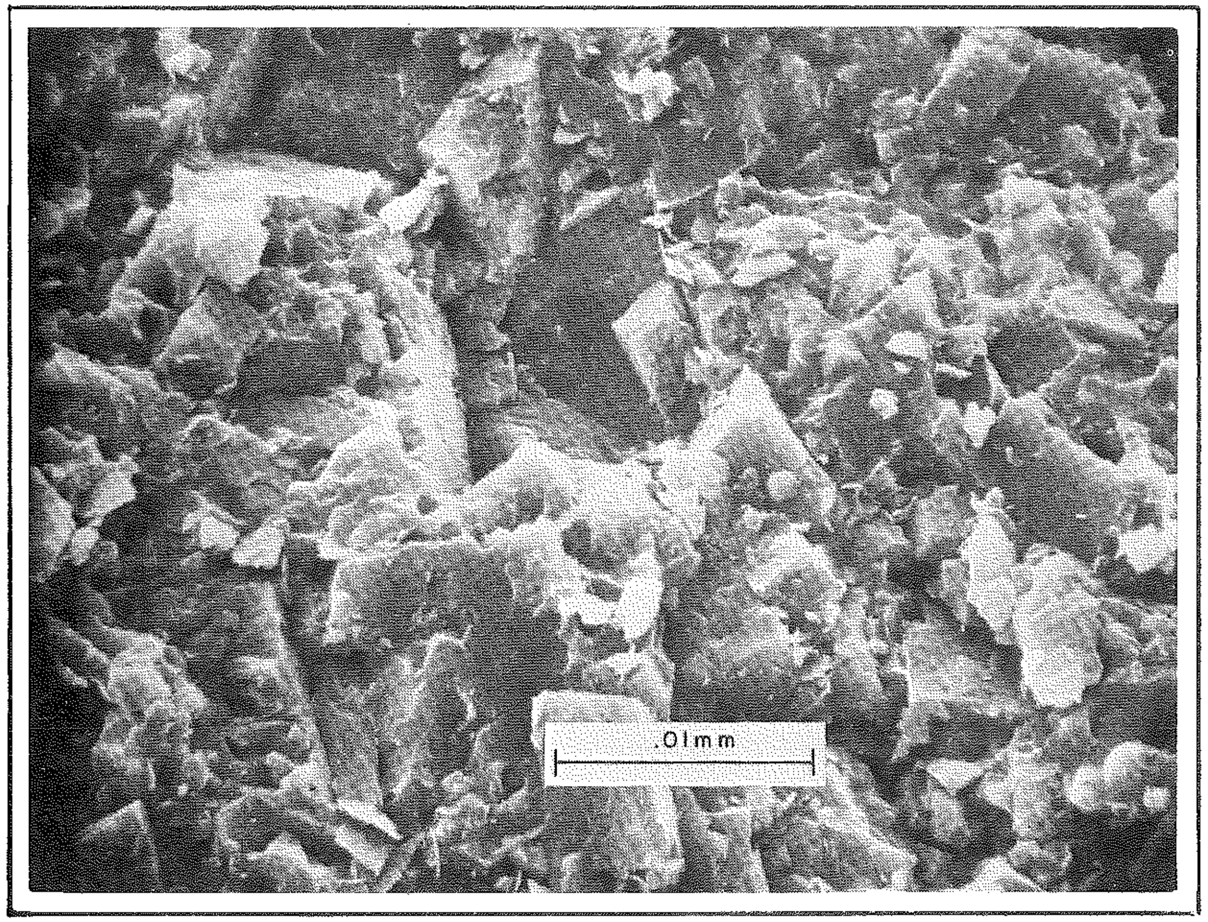


Figure C-4. Highly Expansive Limestone (H5-5); Shows Platyness.

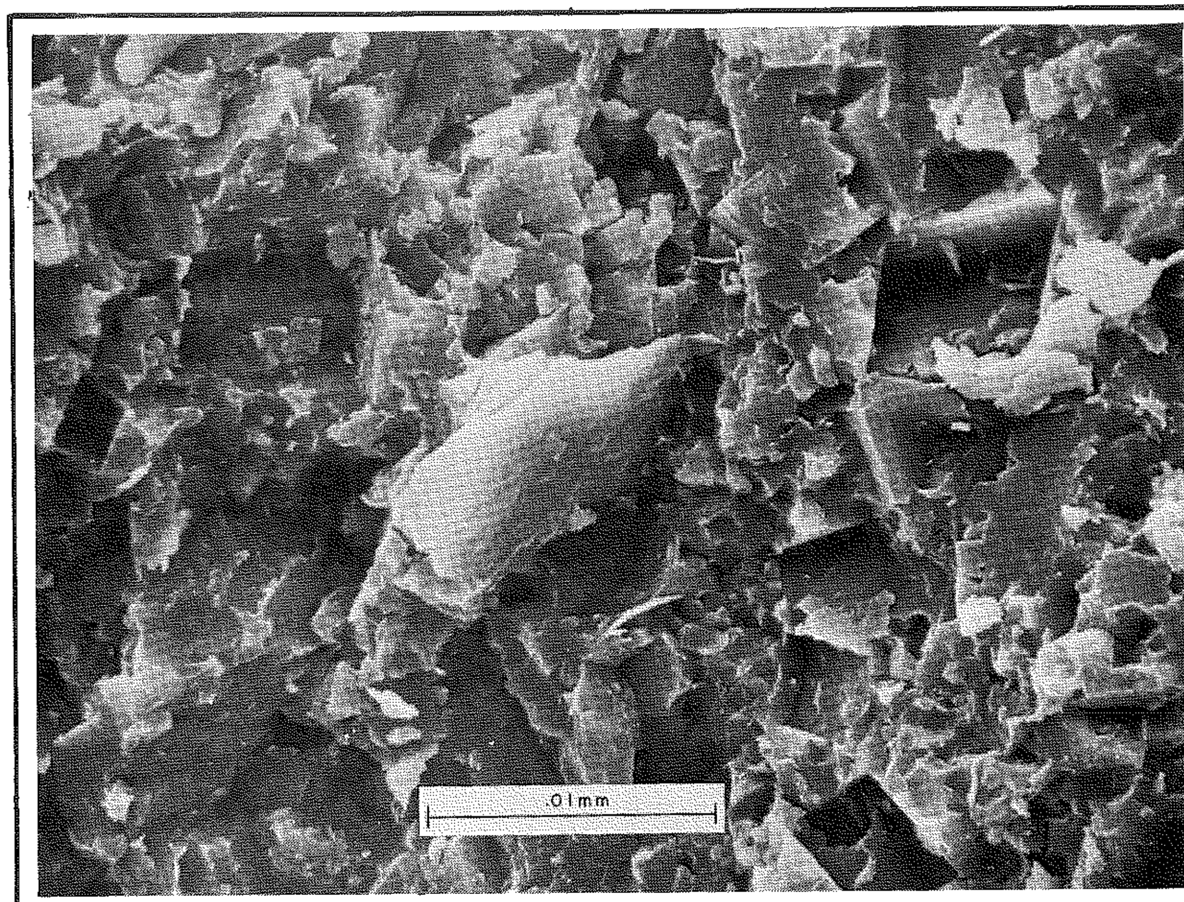


Figure C-5. Highly Expansive Limestone (H5-5); Shows Platyness, Flakiness, and Delamination (not found in good limestones and dolomites).

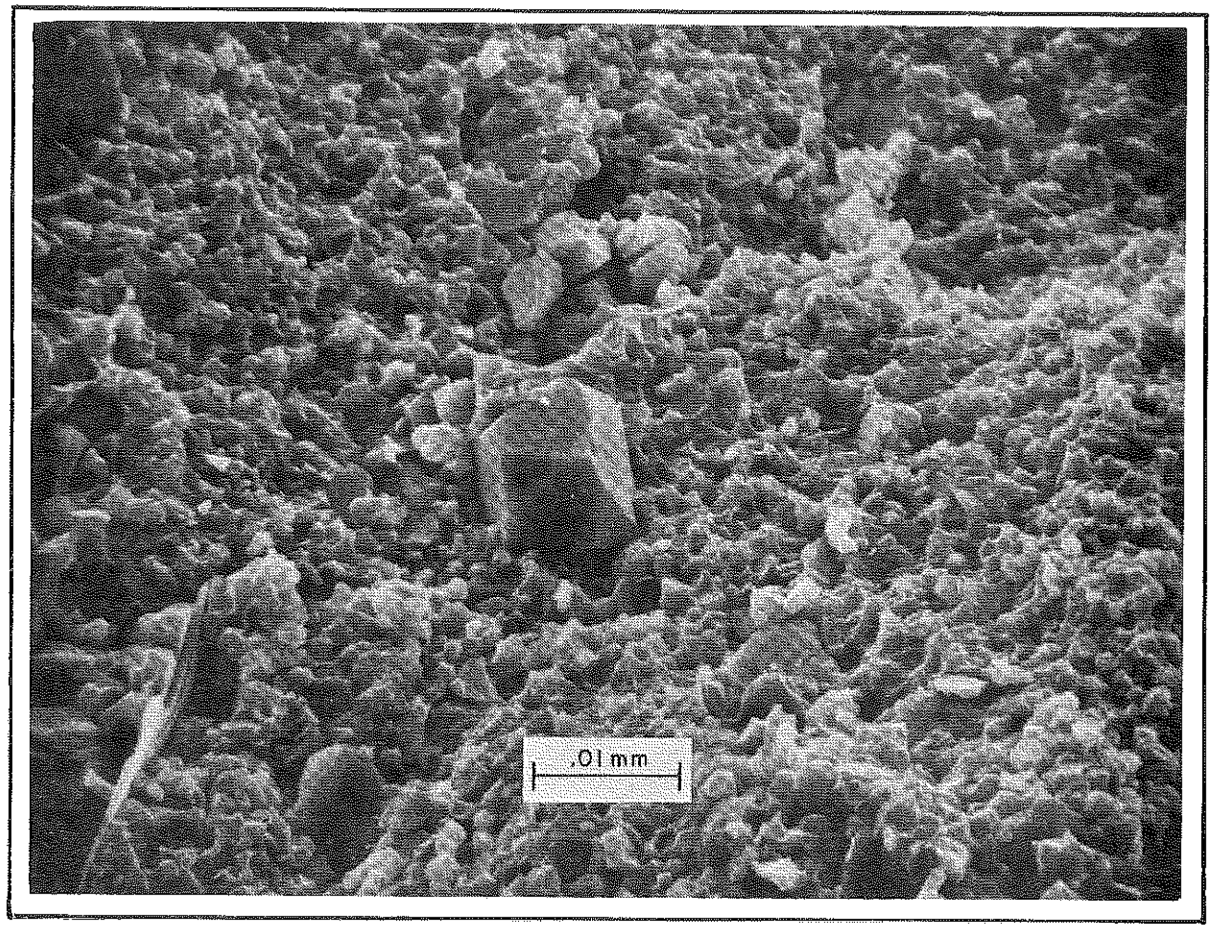


Figure C-6. Non-Expansive Limestone (14-15T); Absence of Platyness and Flakiness.

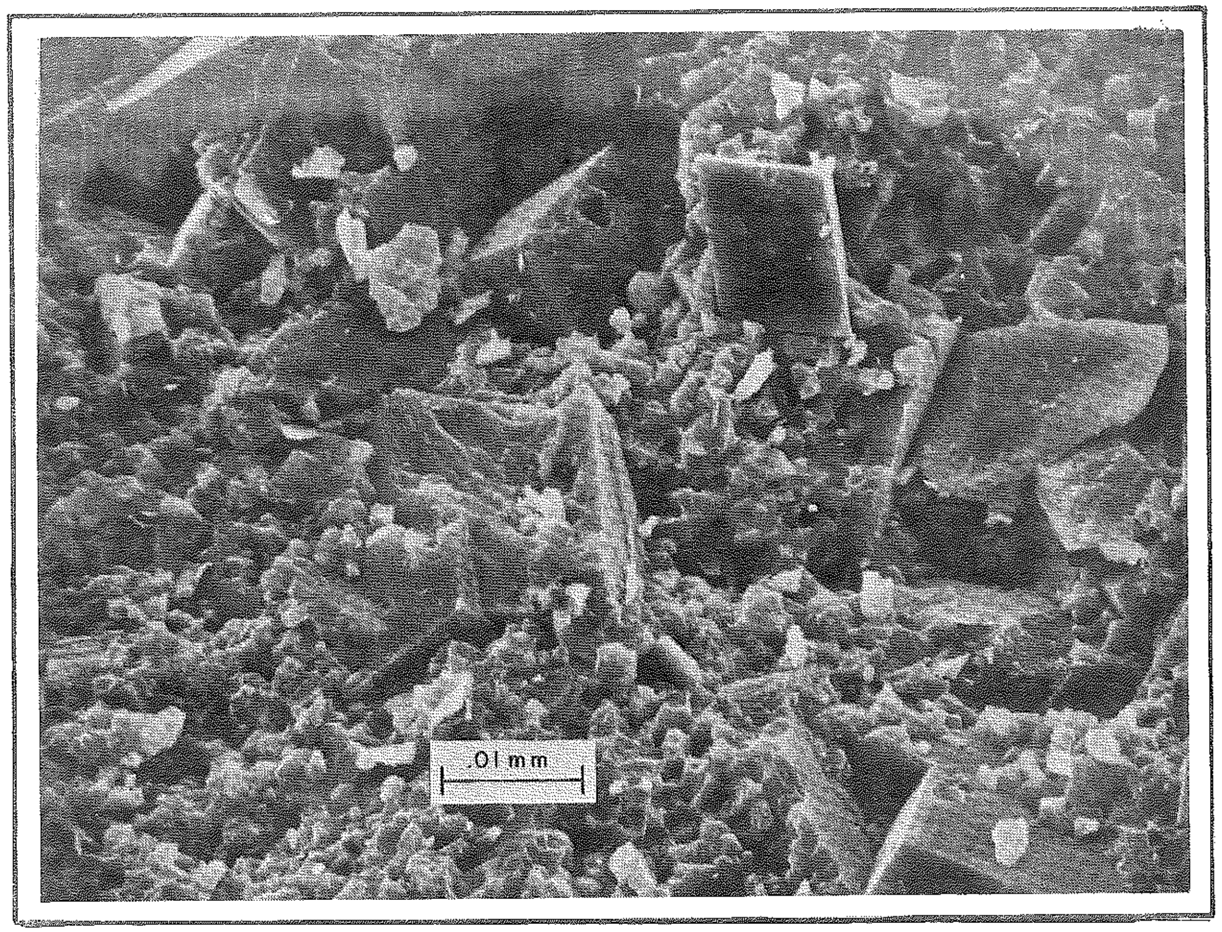


Figure C-7. Non-Expansive Limestone (14-15T). Cleavages appear clean and non-platy.

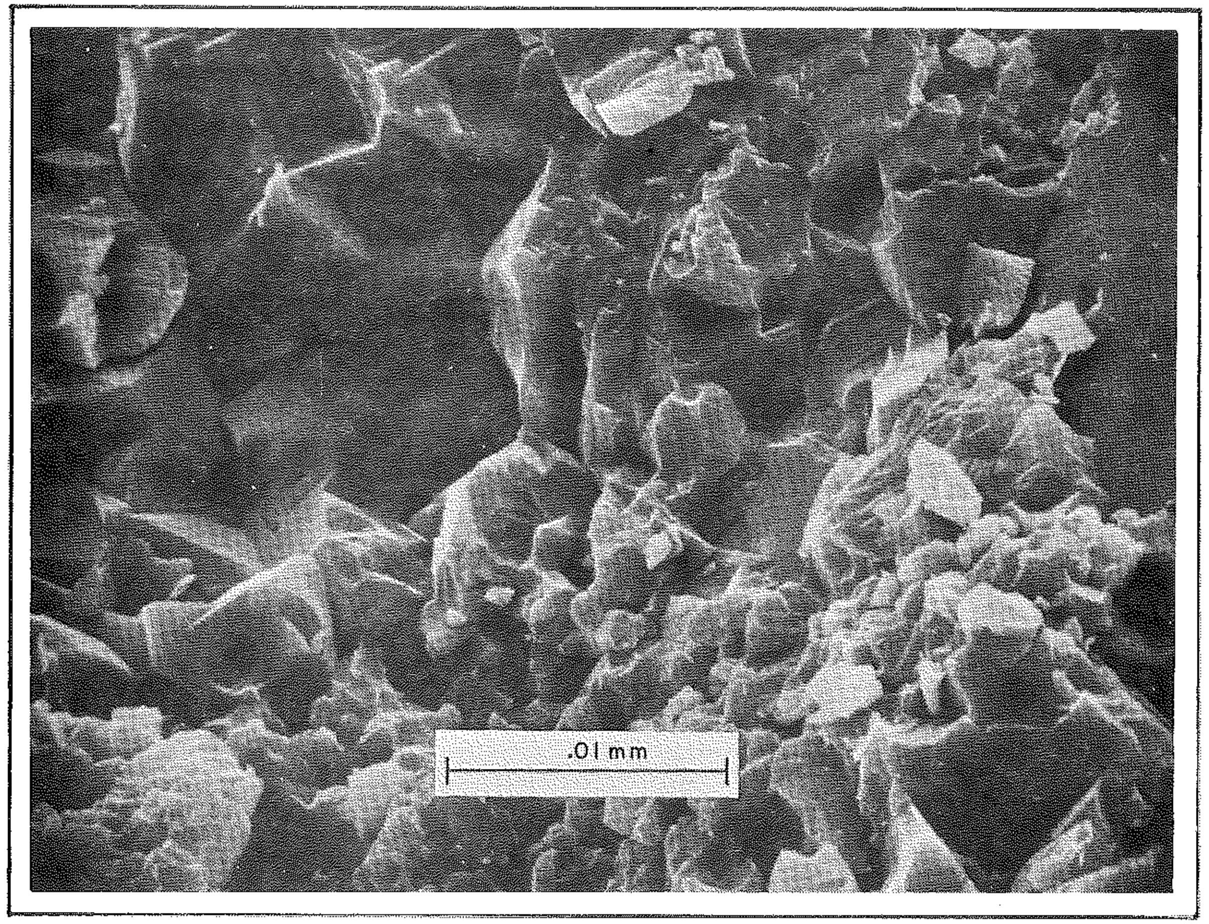


Figure C-8. Non-Expansive Limestone (14-15T). Cleavages appear strong, massive, and non-platy -- non flaky.

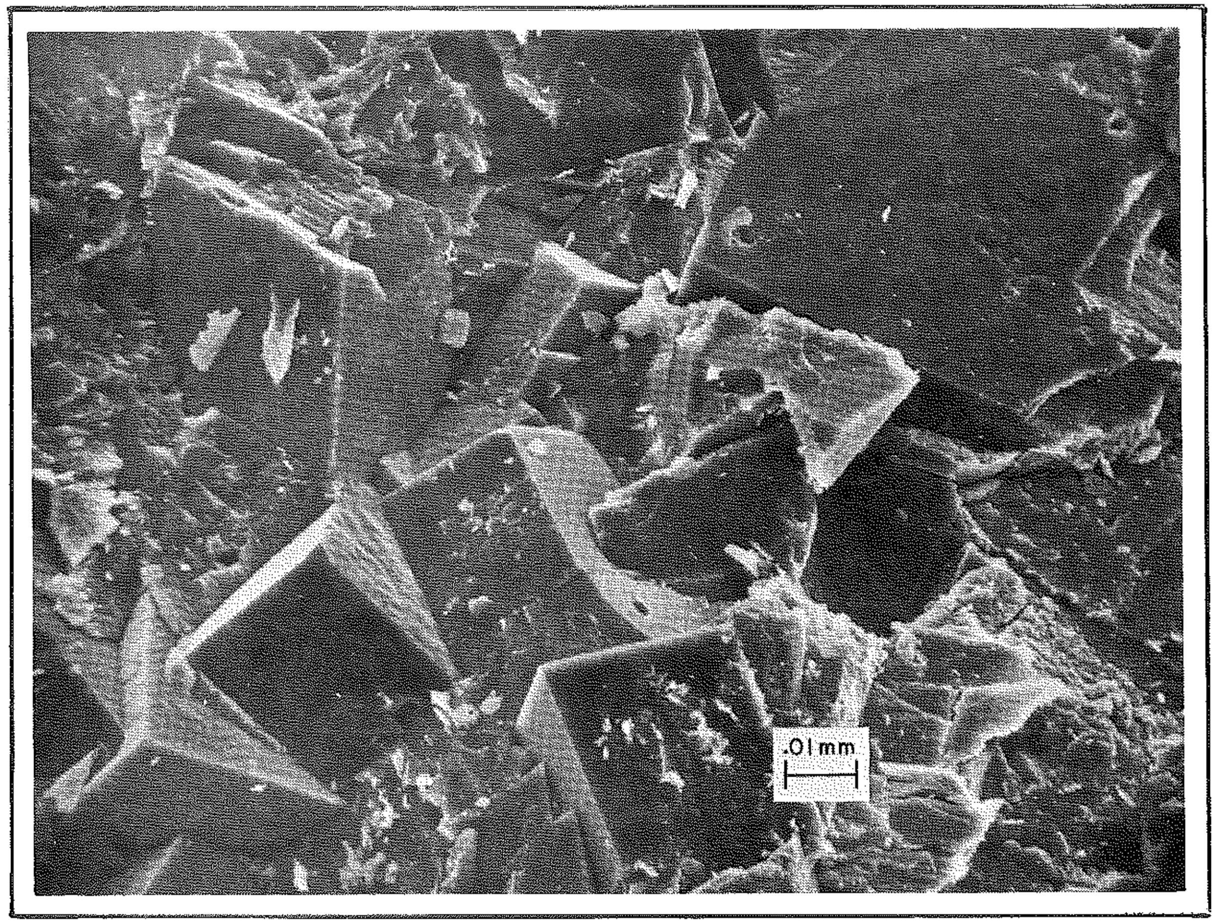


Figure C-9. Non-Expansive Limestone (57-2); Distinct Cleavage. Shows massive structure and great solidity.

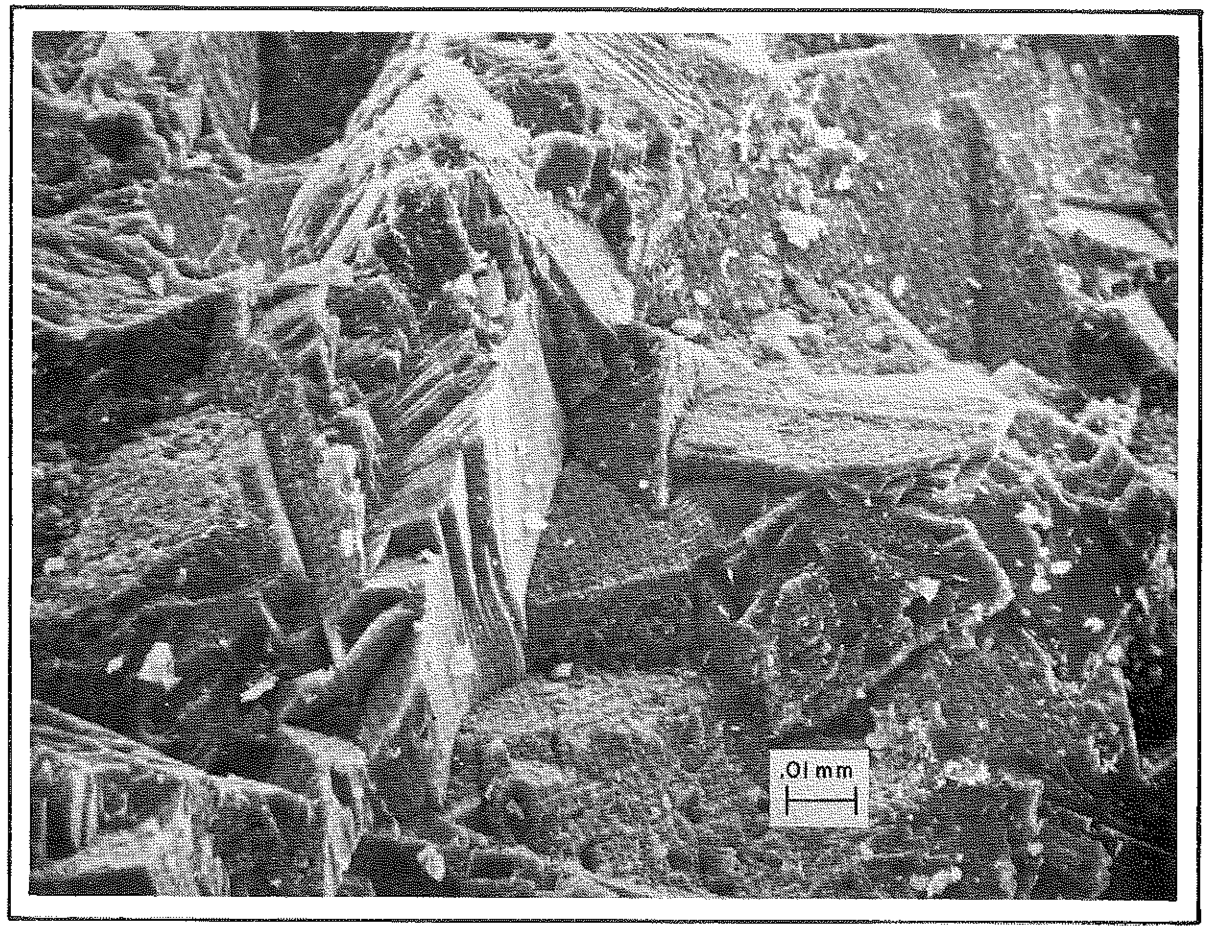


Figure C-10. Non-Expansive Limestone (57-2); Distinct Cleavage. Shows massive structure but apparent disorder or cavitation in cleaved surfaces

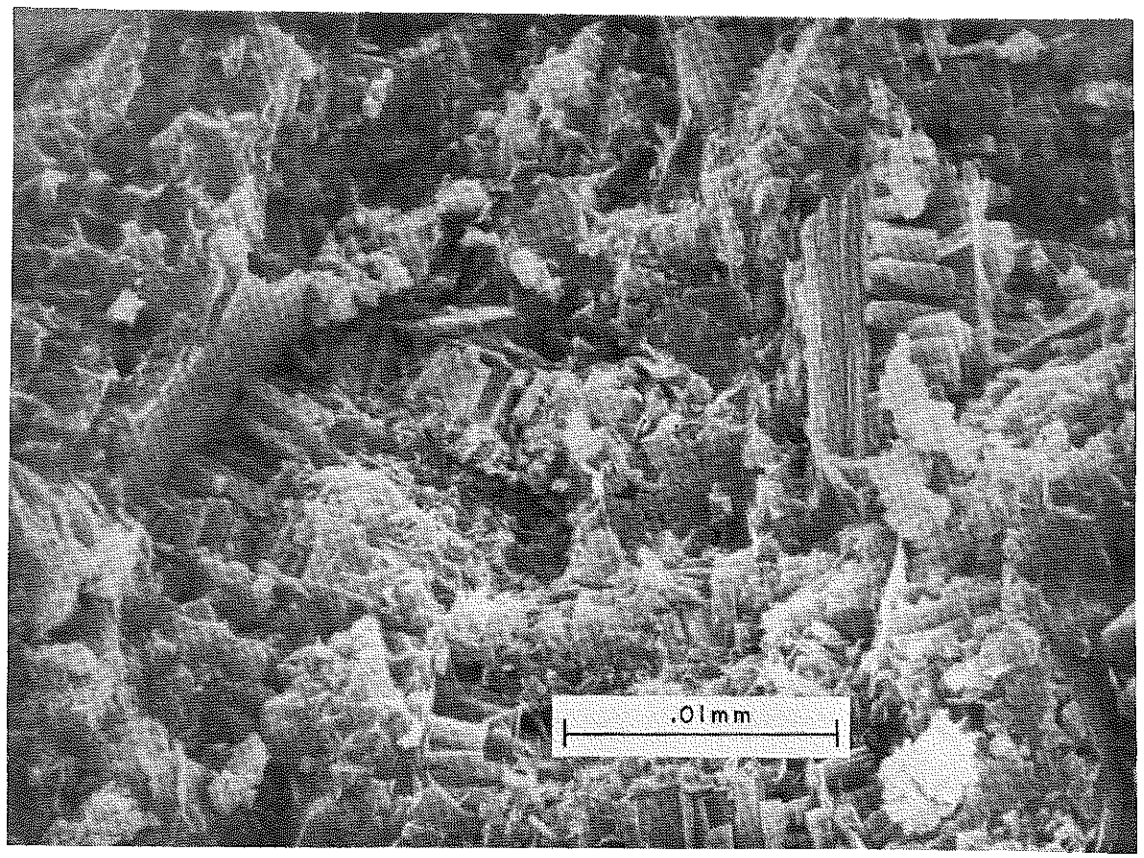


Figure C-11. Expansive Limestone ((116-11). Shows disorder in crystallization and texture; porosity and weakness are apparent.

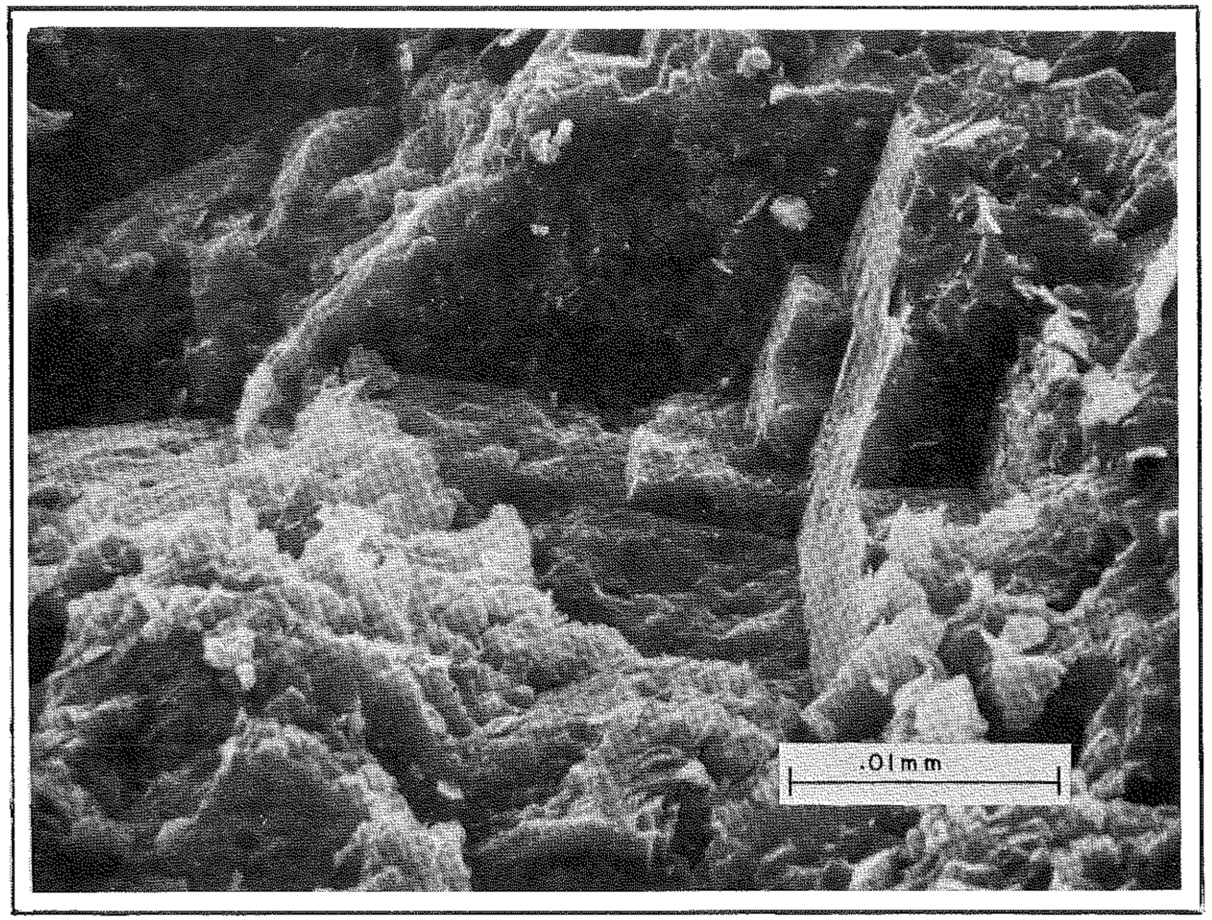


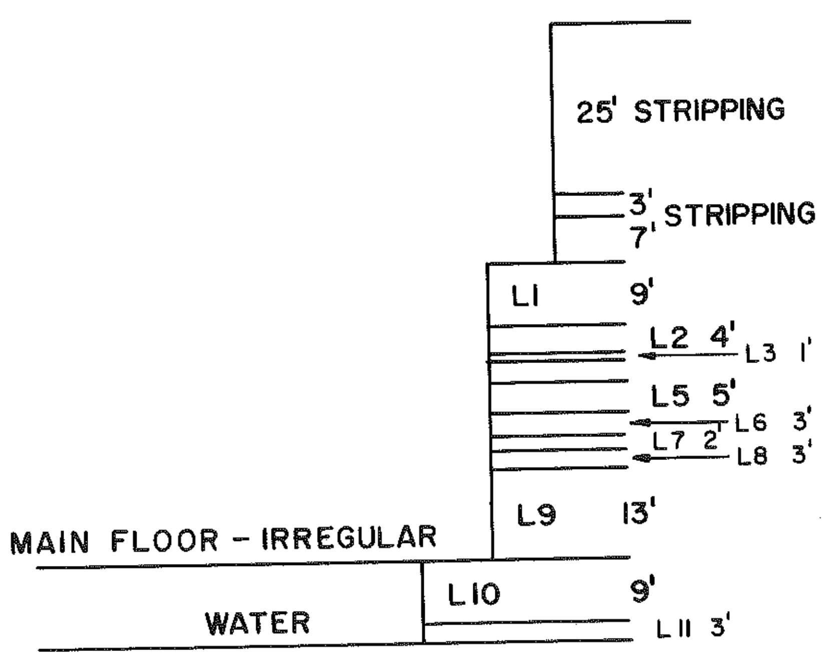
Figure C-12. Expansive Limestone (116-11). Shows thin cleavage plates and flakiness.

APPENDIX D

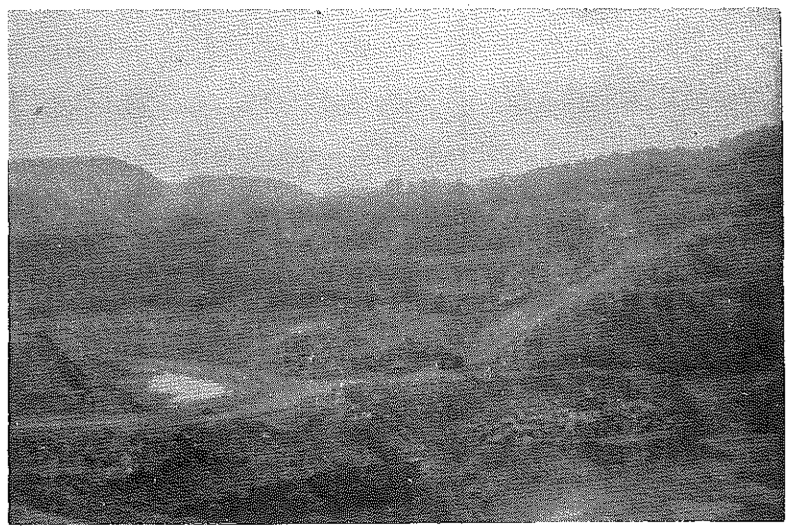
QUARRY PROFILES
AND PHOTOGRAPHS

SOURCE HS

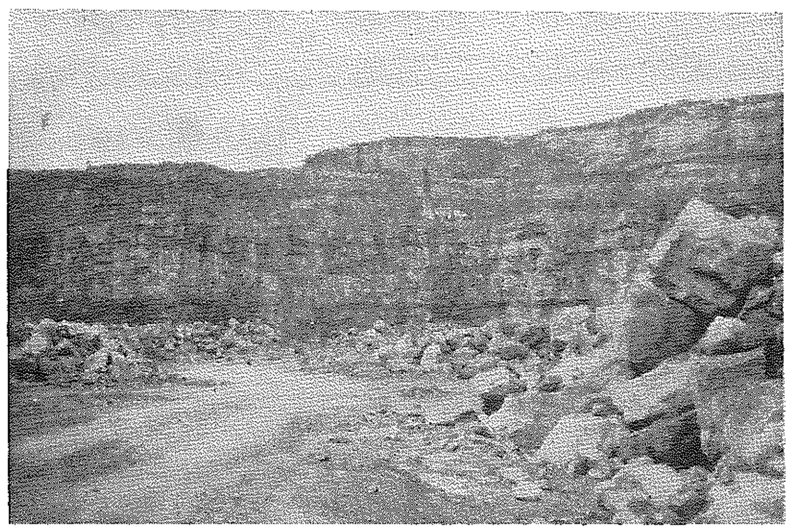
EXPANSIVE POTENTIAL
5-11-77



SOURCE NO. 2
THREE RIVERS ROCK
LIVINGSTON COUNTY
MISSISSIPPIAN AGE

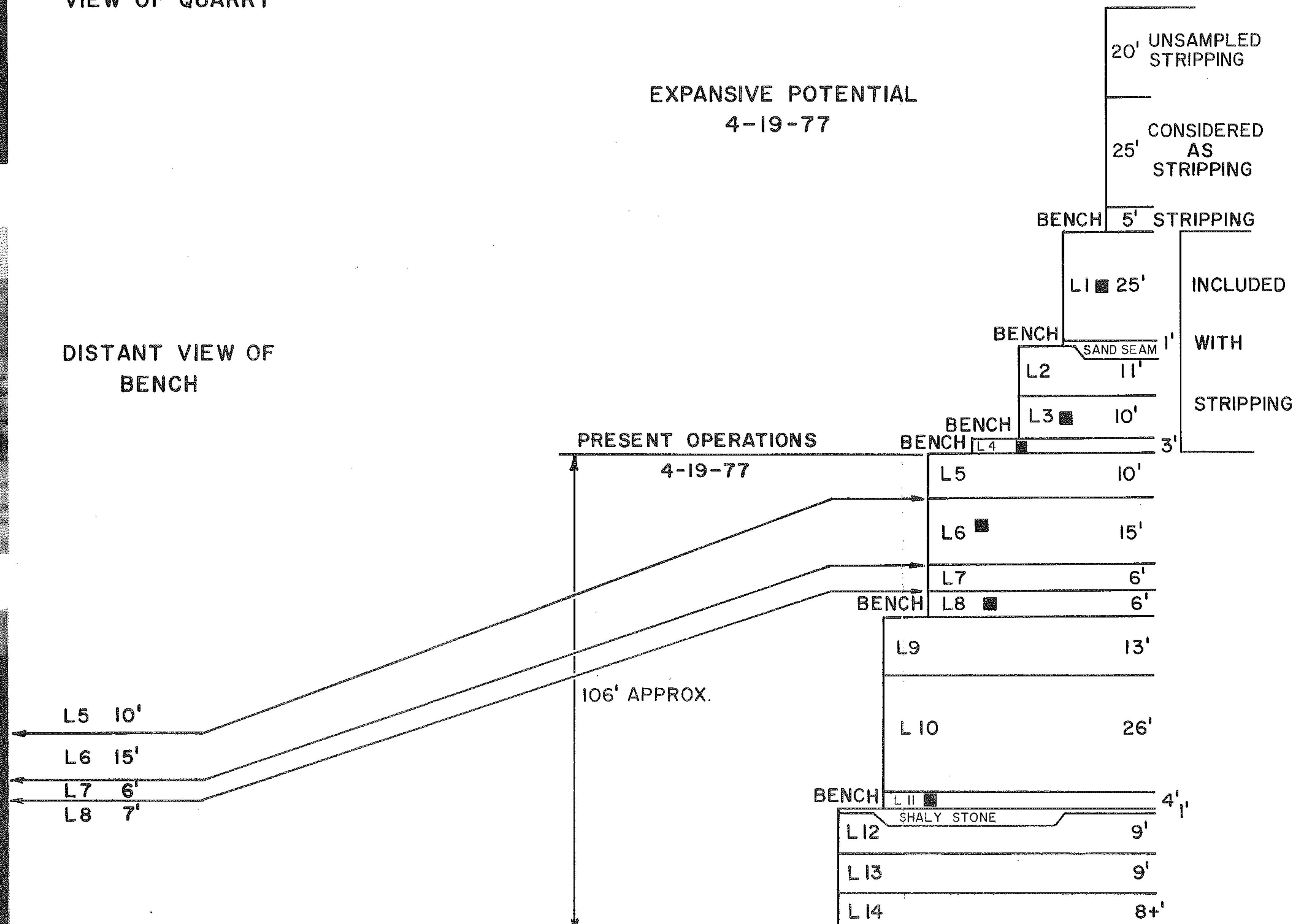


DISTANT OVERALL VIEW OF QUARRY



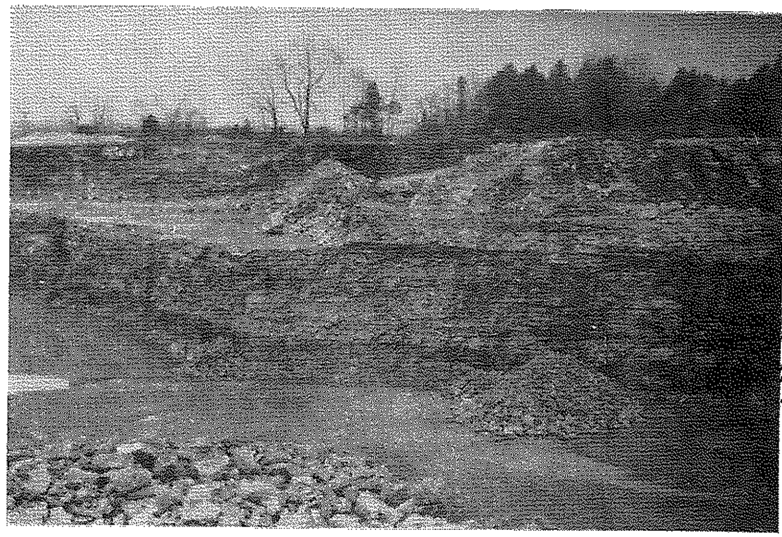
DISTANT VIEW OF BENCH

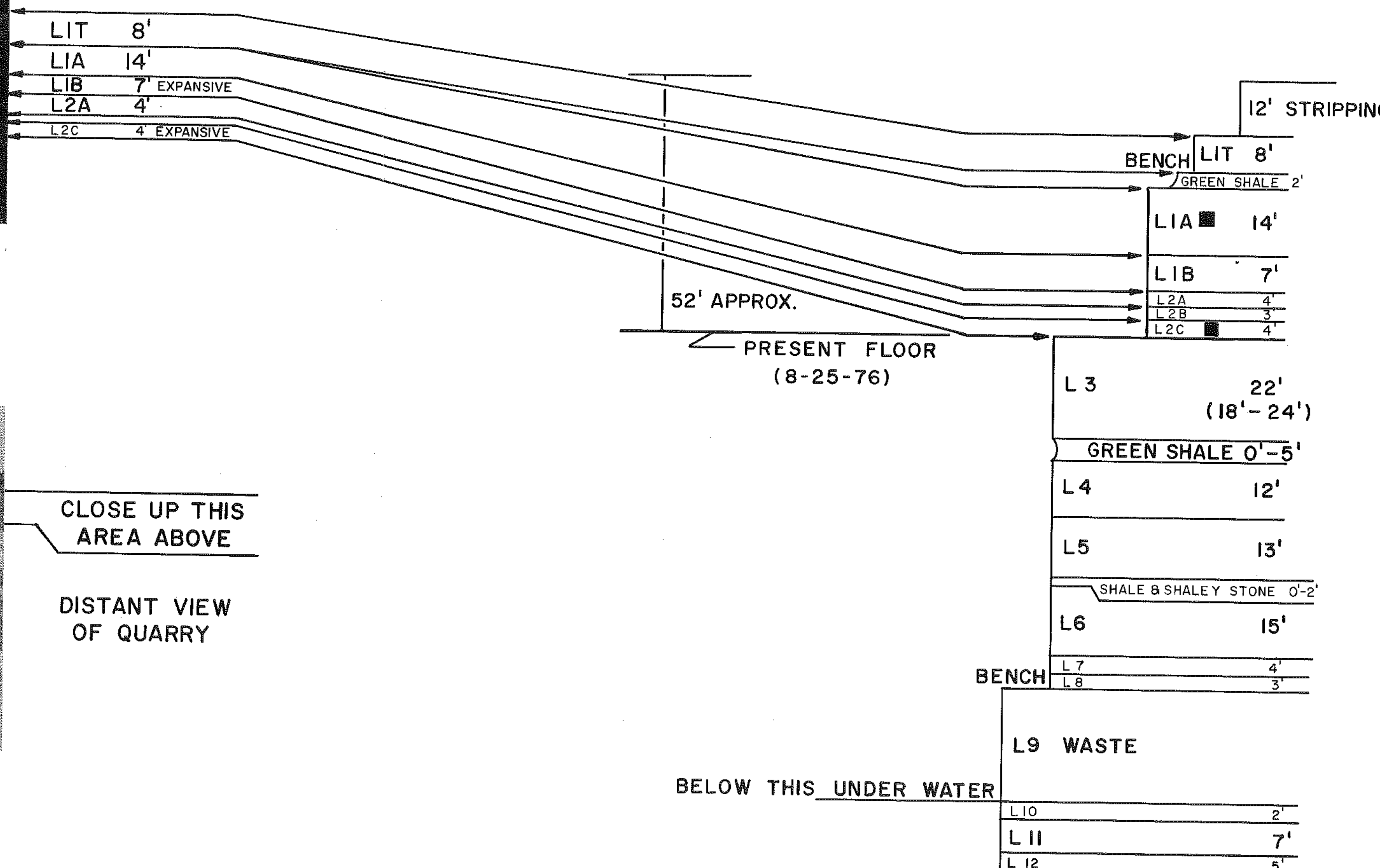
EXPANSIVE POTENTIAL 4-19-77

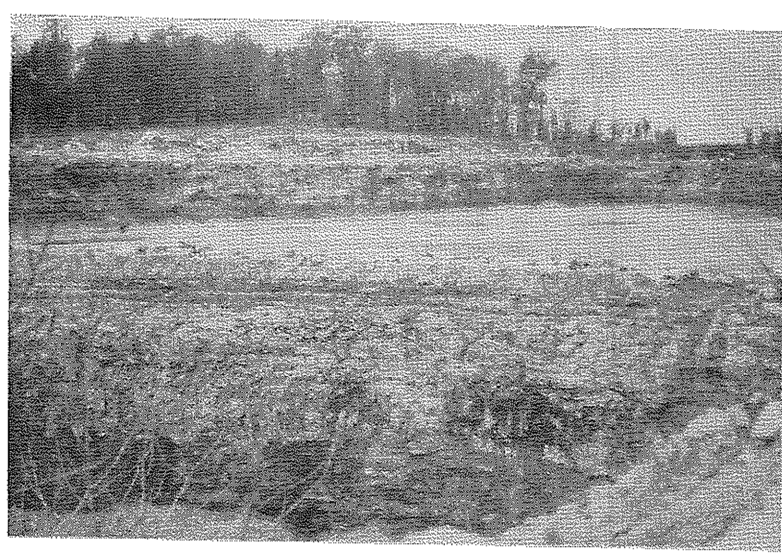


SOURCE NO. 7
HOPKINSVILLE AGGREGATE
CHRISTIAN COUNTY
MISSISSIPPIAN AGE

EXPANSIVE POTENTIAL
4-19-77

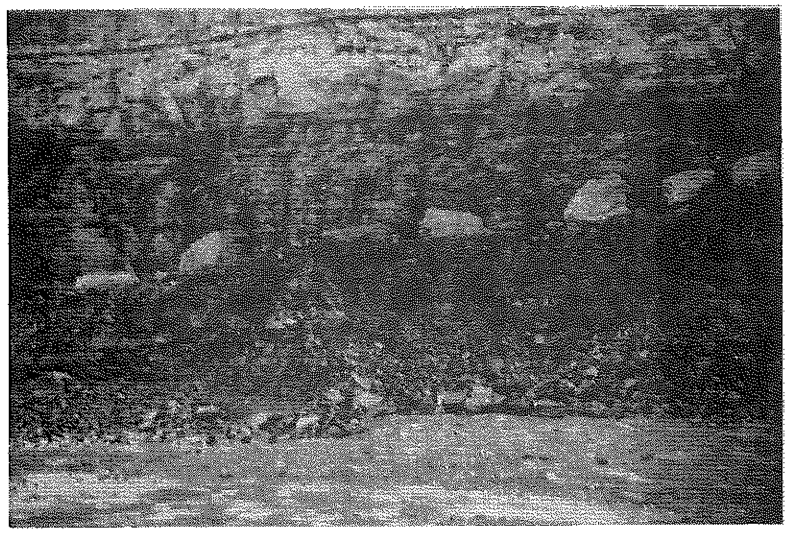






CLOSE UP THIS AREA ABOVE

DISTANT VIEW OF QUARRY

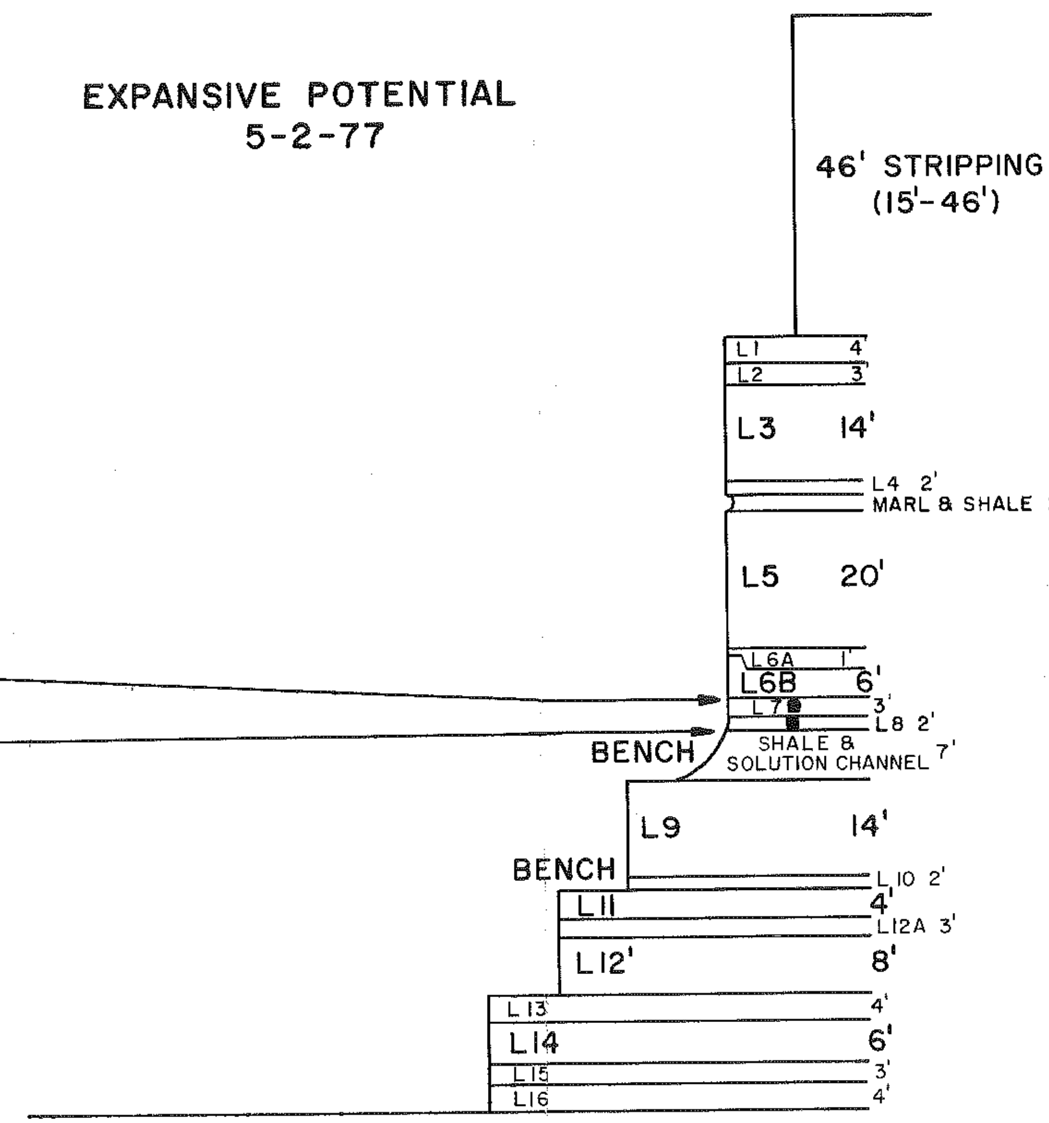


VIEW OF RAMP AT CHRISTIAN QUARRY
CLOSE UP BELOW
(WHITE LINE IS TAPE MEASURE)

SOURCE NO. 9
CHRISTIAN QUARRY
CHRISTIAN COUNTY
MISSISSIPPIAN AGE

EXPANSIVE POTENTIAL
5-2-77

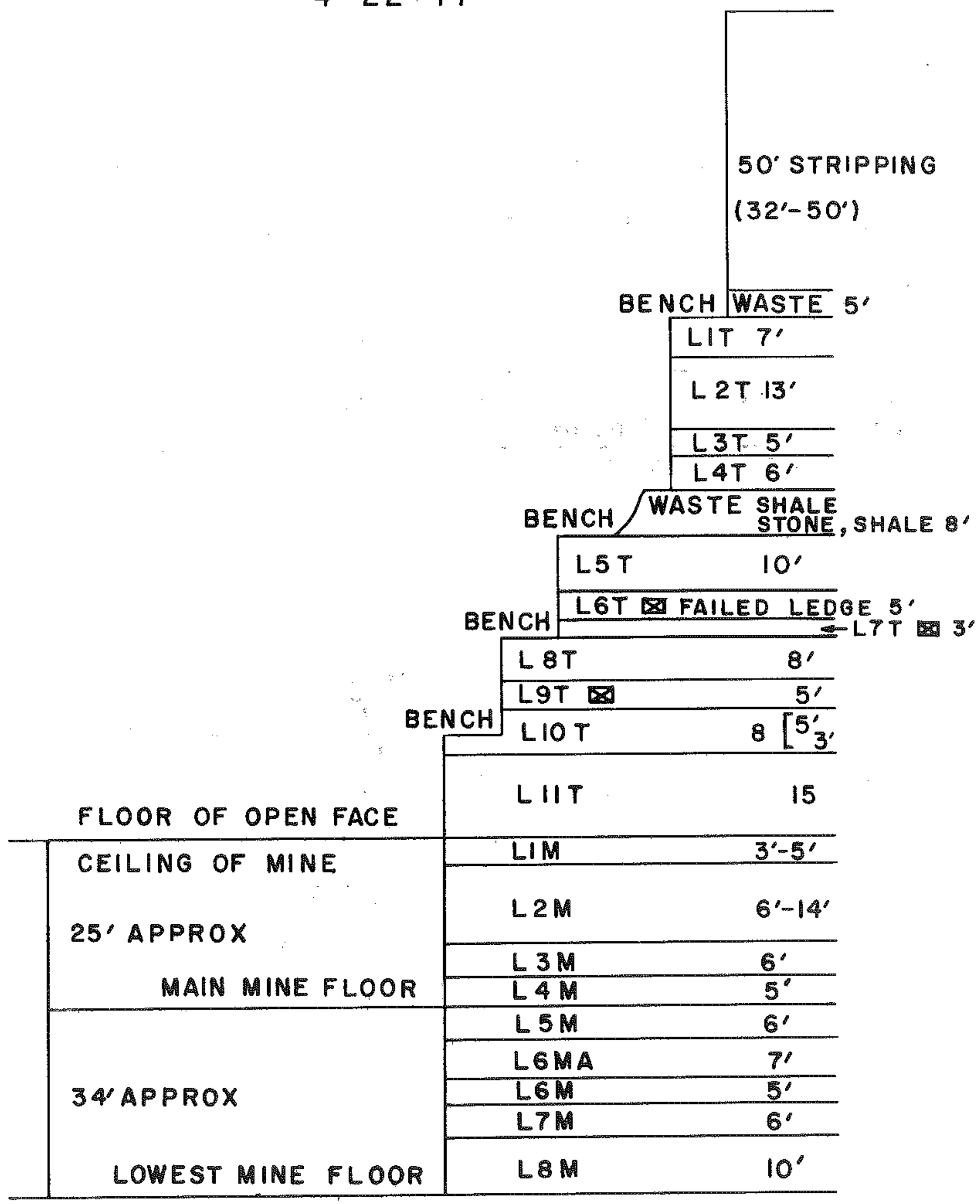
L7 3'
L8 2'



SOURCE II

EXPANSIVE POTENTIAL

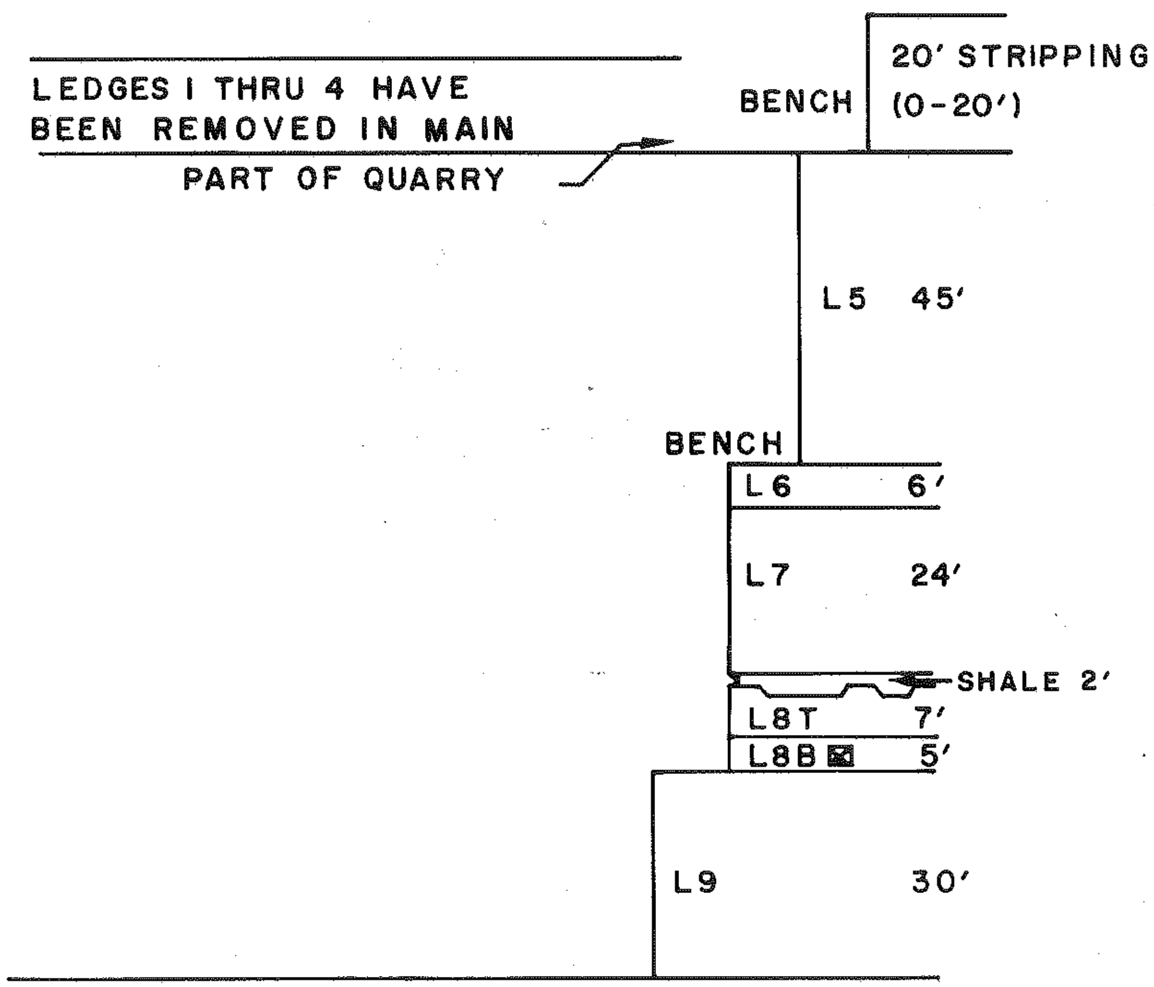
4-22-77

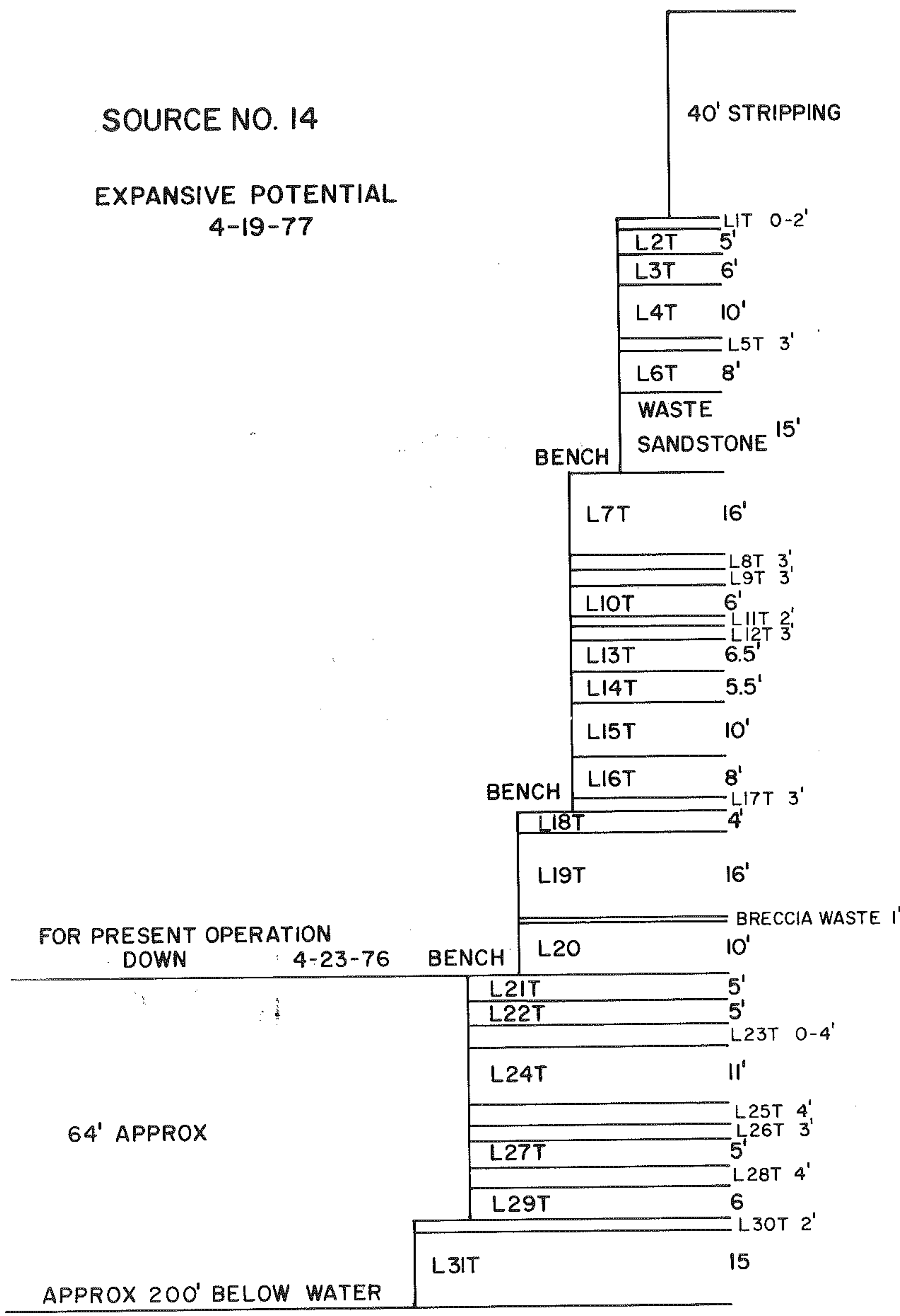


SOURCE 12

EXPANSIVE POTENTIAL

5-2-77

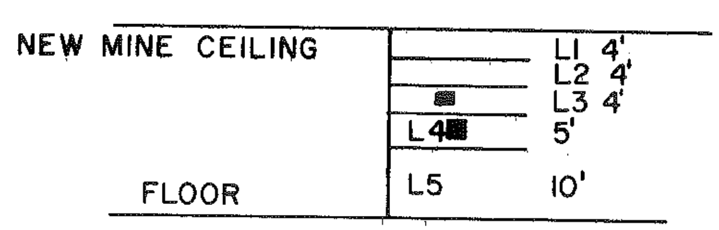




SOURCE NO. 14
EXPANSIVE POTENTIAL
4-19-77
40' STRIPPING
L1T 0-2'
L2T 5'
L3T 6'
L4T 10'
L5T 3'
L6T 8'
WASTE
SANDSTONE 15'
BENCH
L7T 16'
L8T 3'
L9T 3'
L10T 6'
L11T 2'
L12T 3'
L13T 6.5'
L14T 5.5'
L15T 10'
L16T 8'
BENCH
L17T 3'
L18T 4'
L19T 16'
BRECCIA WASTE 1'
FOR PRESENT OPERATION
DOWN 4-23-76
BENCH
L20 10'
L21T 5'
L22T 5'
L23T 0-4'
L24T 11'
L25T 4'
L26T 3'
64' APPROX
L27T 5'
L28T 4'
L29T 6
L30T 2'
L31T 15
APPROX 200' BELOW WATER

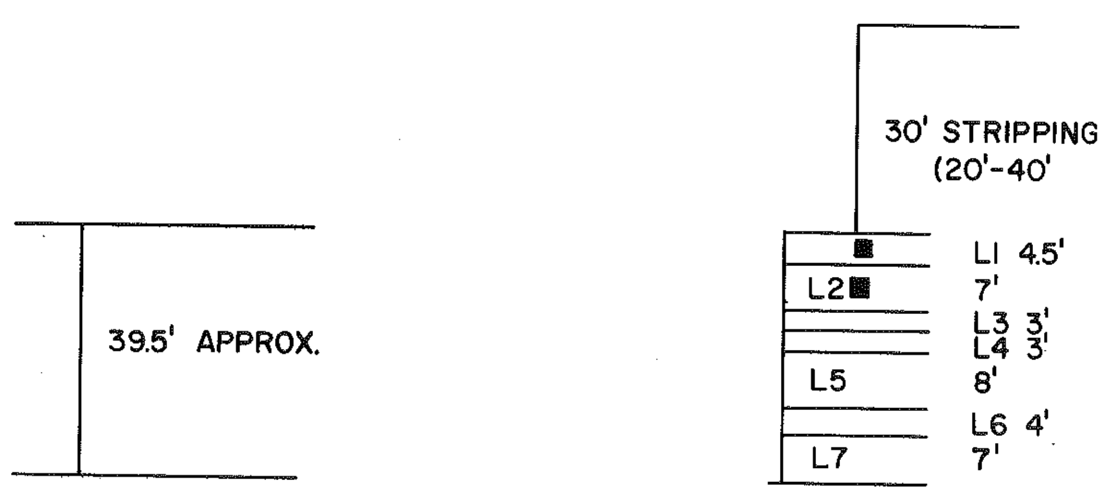
SOURCE 13

EXPANSIVE POTENTIAL
5-2-77

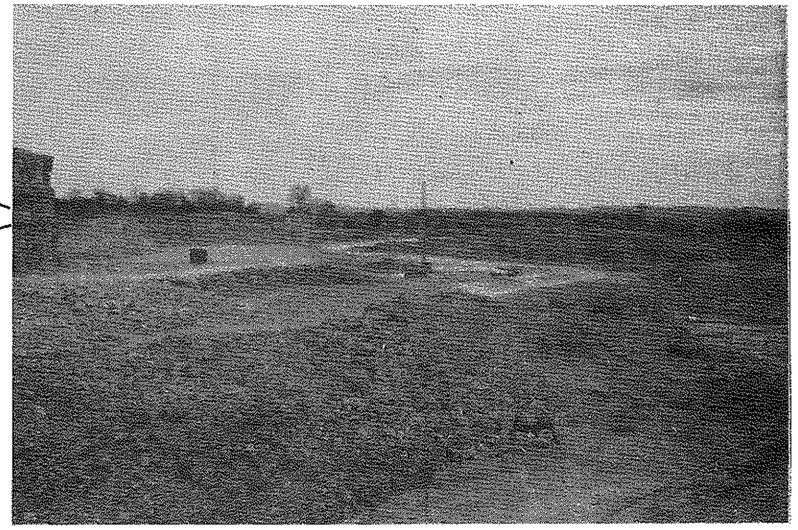


SOURCE NO. 15

EXPANSIVE POTENTIAL
4-19-77



LIA - TOP OF BENCH

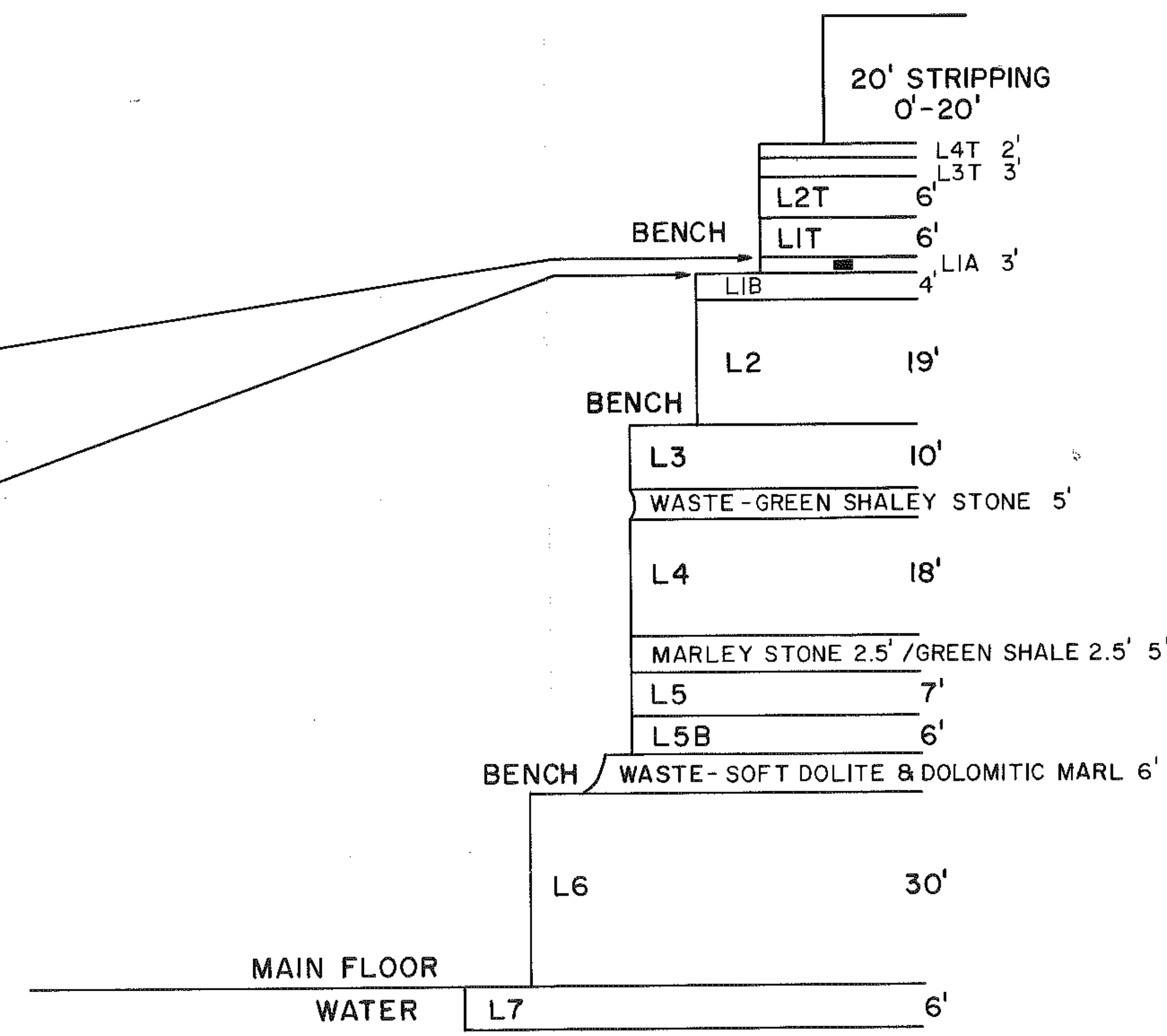


DISTANT VIEW OF QUARRY

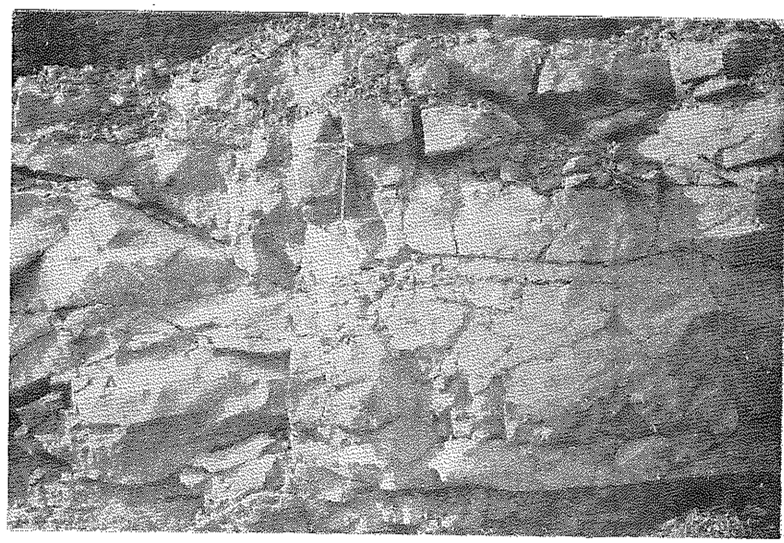
SOURCE NO. 16
WARREN COUNTY
(BOWLING GREEN, KY.)
MISSISSIPPIAN AGE

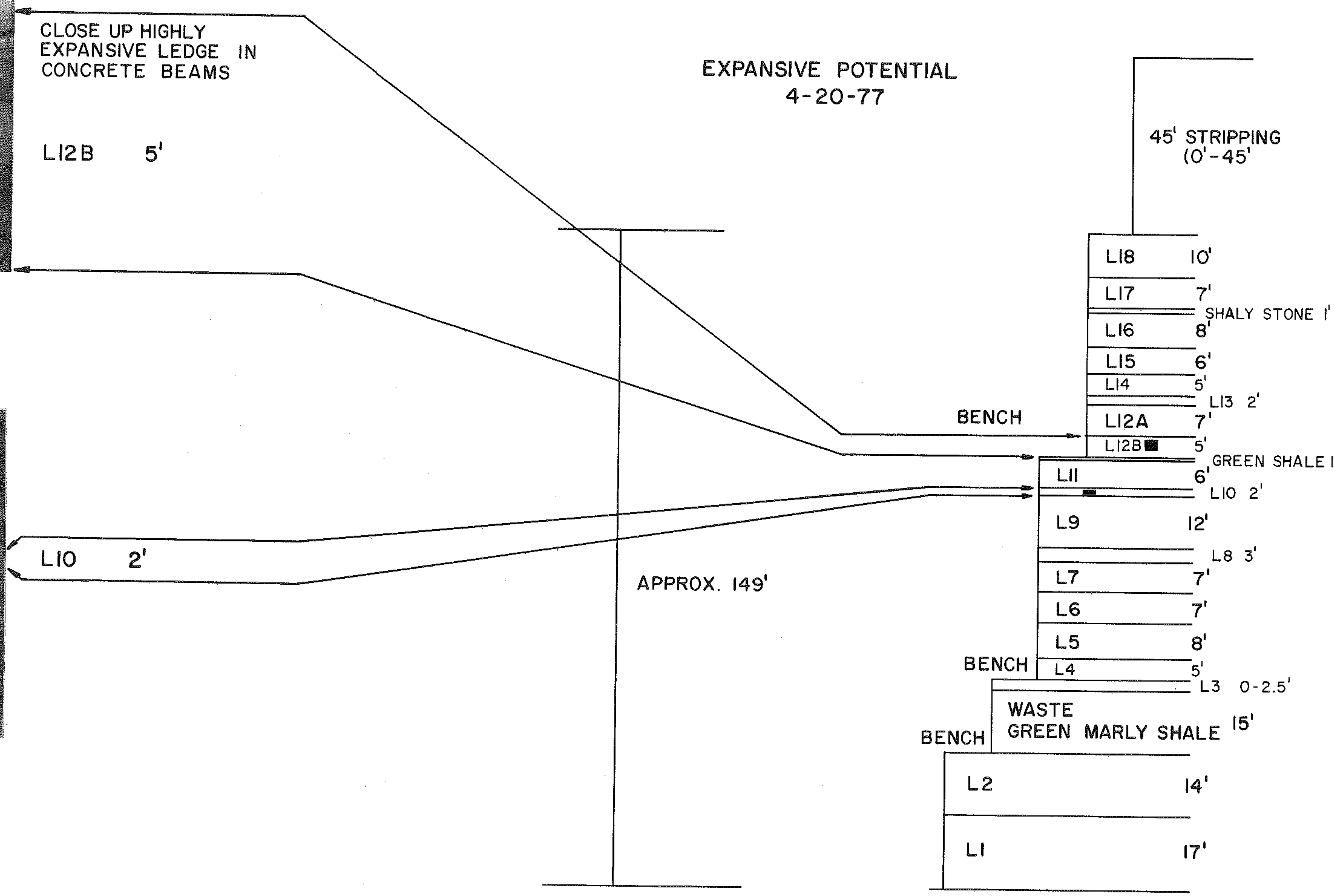
EXPANSIVE POTENTIAL
4-20-77

LIA 3'

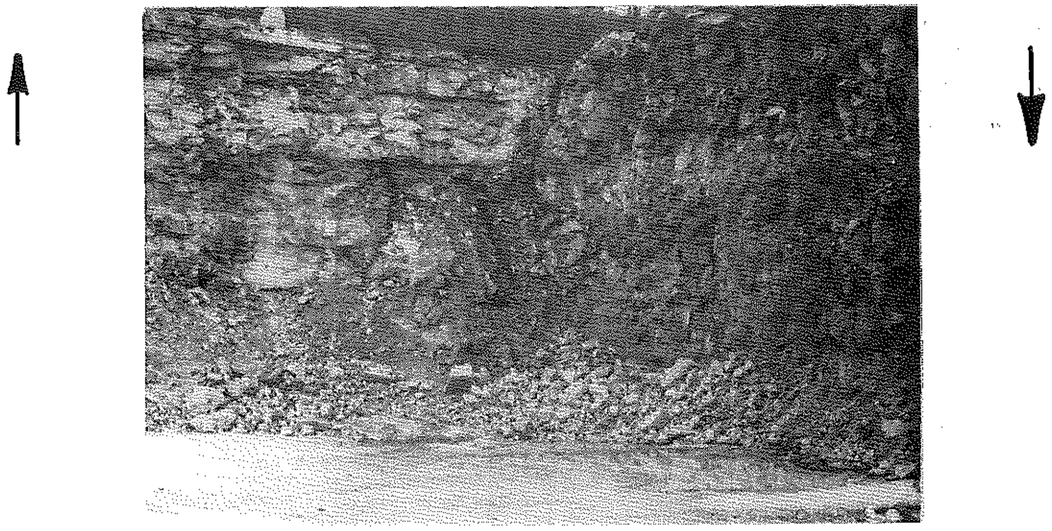


SOURCE NO. 20
STATE CONTRACTING
EDMONSON COUNTY
MISSISSIPPIAN AGE



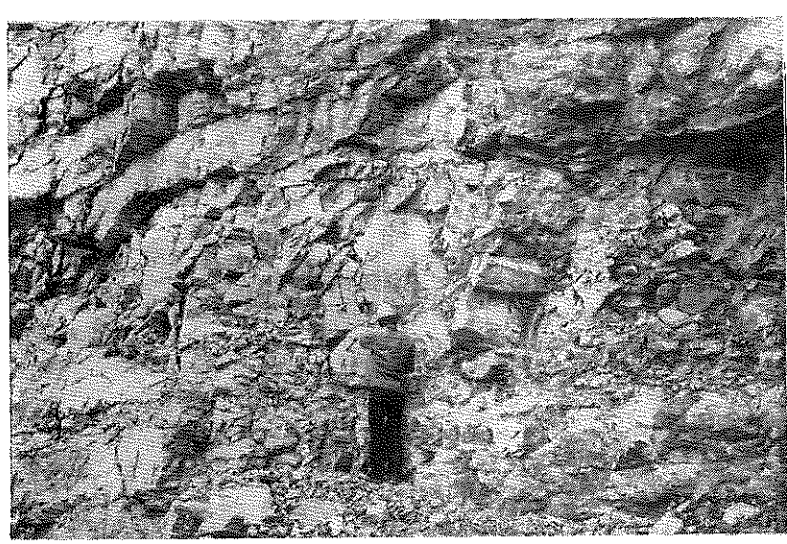


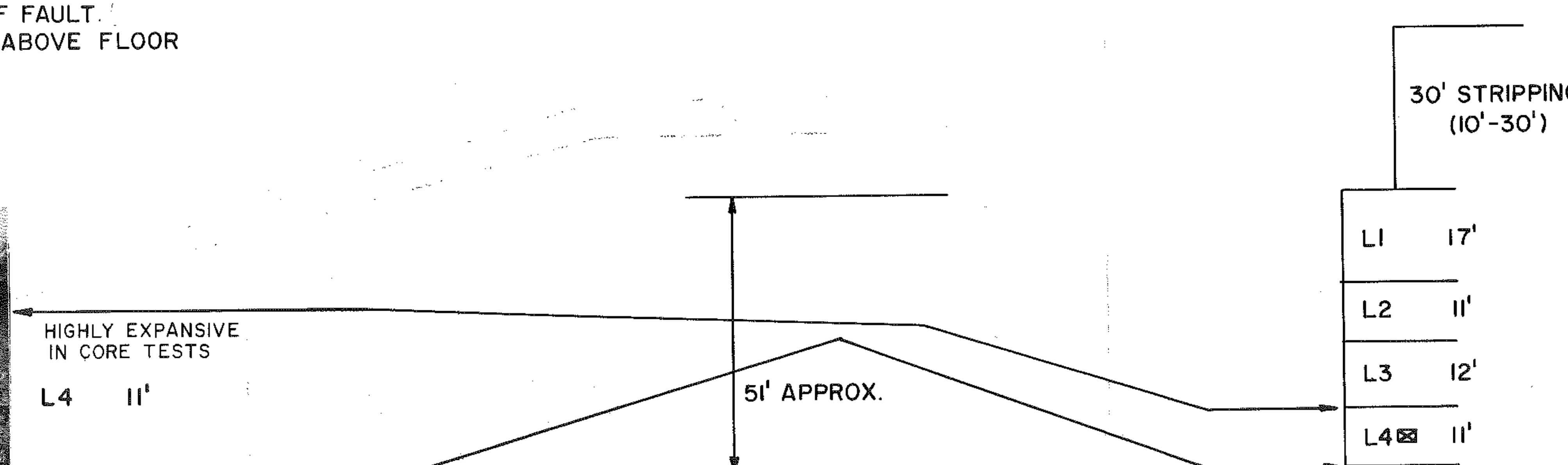
SOURCE NO. 22E
KY. STONE
EAST SITE
SIMPSON COUNTY
MISSISSIPPIAN AGE



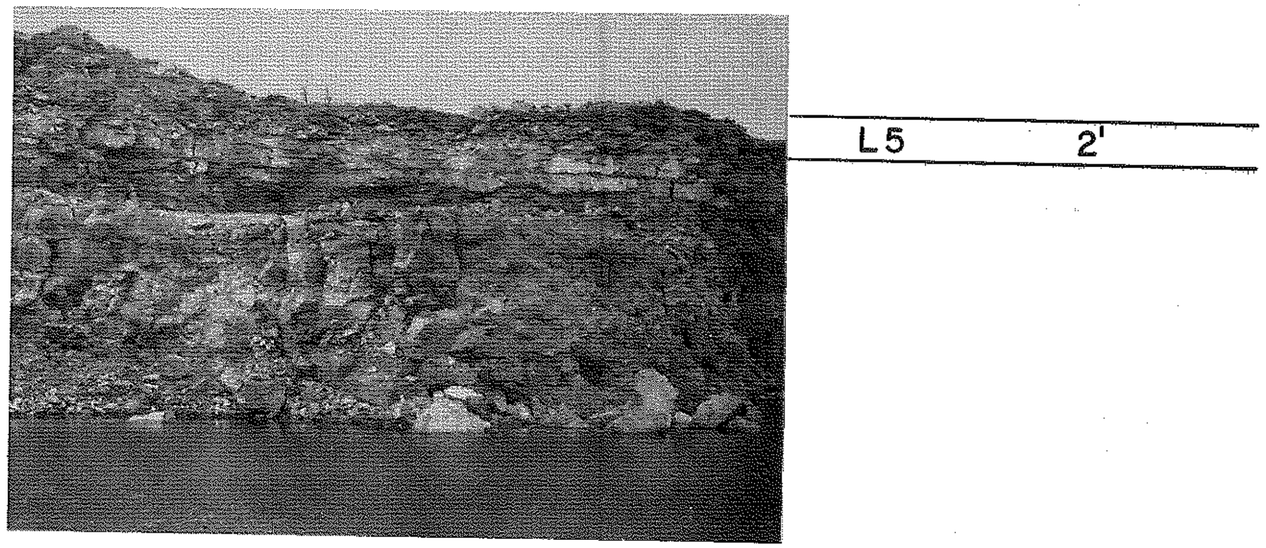
CLASSIC FAULT RUNS THROUGH EAST QUARRY SITE WITH APPROXIMATELY 8' DISPLACEMENT–PICTURE TAKEN DOWN STRIKE OF FAULT.
AN EXTRA LEDGE IS PRESENT ABOVE FLOOR ON UPTHROWN WALL.

EXPANSIVE POTENTIAL
4-20-77

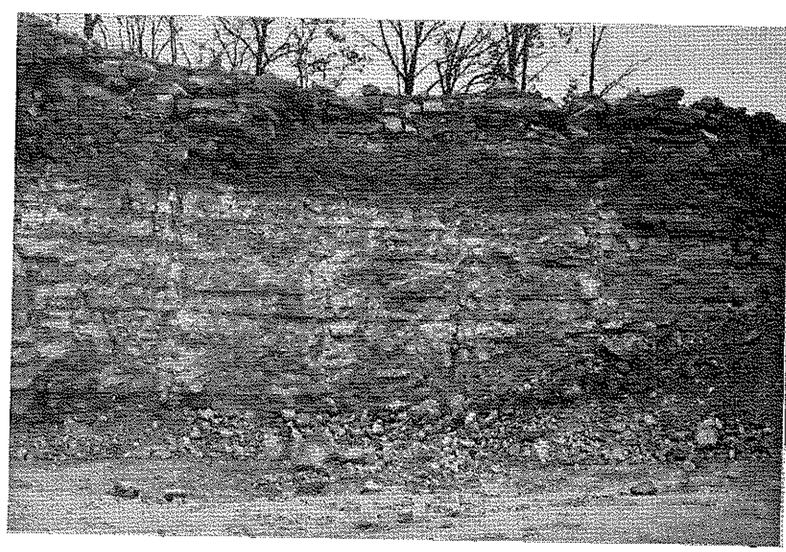


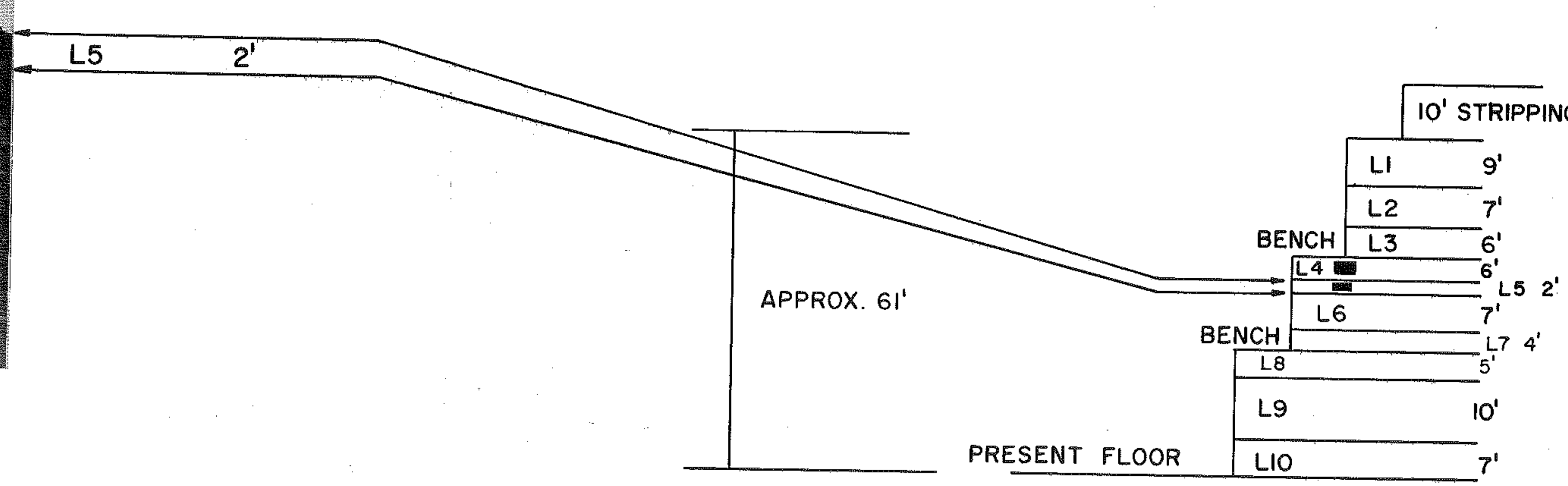


SOURCE NO. 22W
KY. STONE
WEST SITE
SIMPSON COUNTY
MISSISSIPPIAN AGE



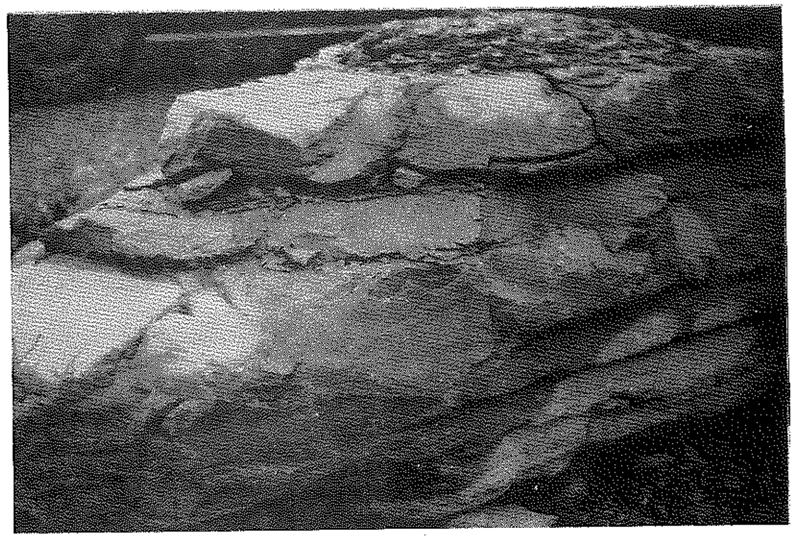
EXPANSIVE POTENTIAL
4-20-77





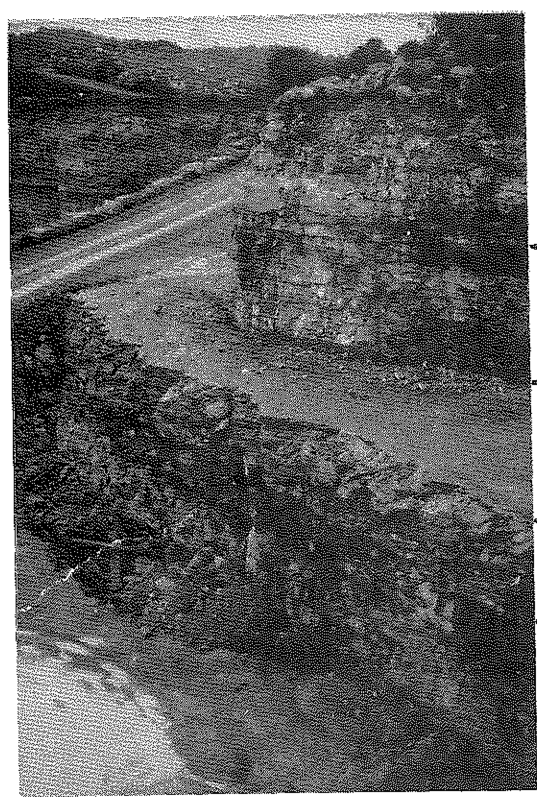
FAULTING IN AREA MAKES TRACING LEDGES THROUGH THE TWO SITES DIFFICULT. SEPARATE LOGS WERE MADE.

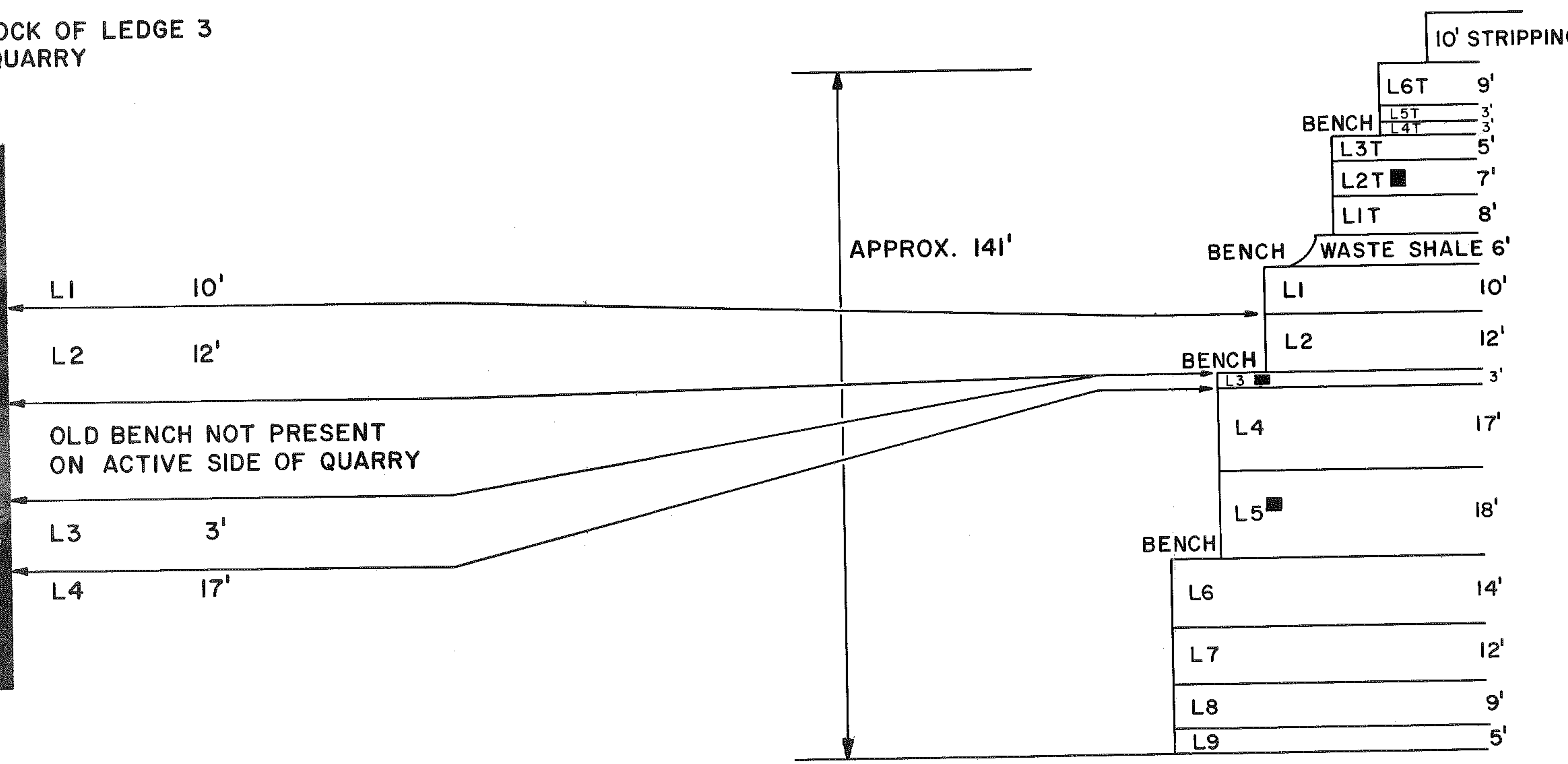
SOURCE NO. 23
KY STONE
LOGAN COUNTY
MISSISSIPPIAN AGE



WEATHERED BLOCK OF LEDGE 3
AT QUARRY

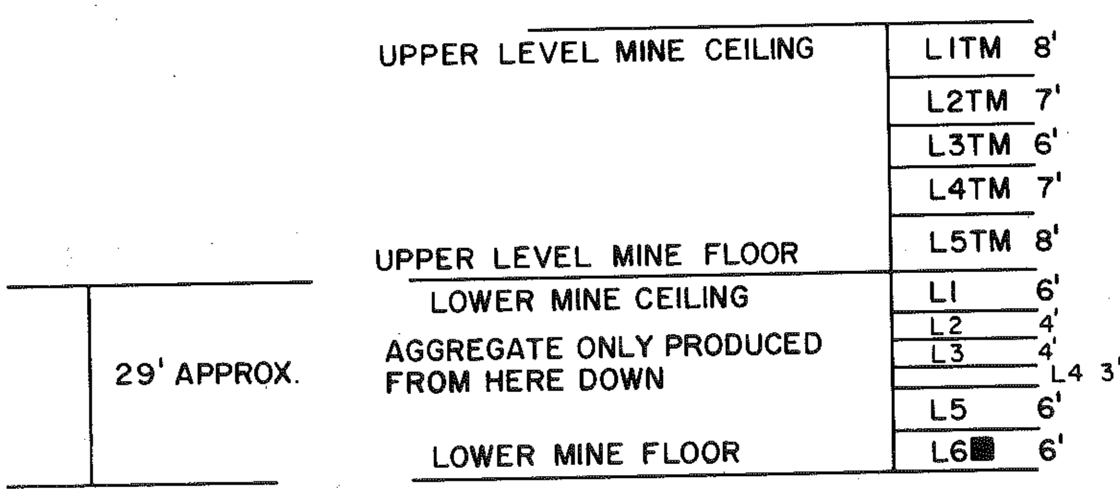
EXPANSIVE POTENTIAL
4-20-77



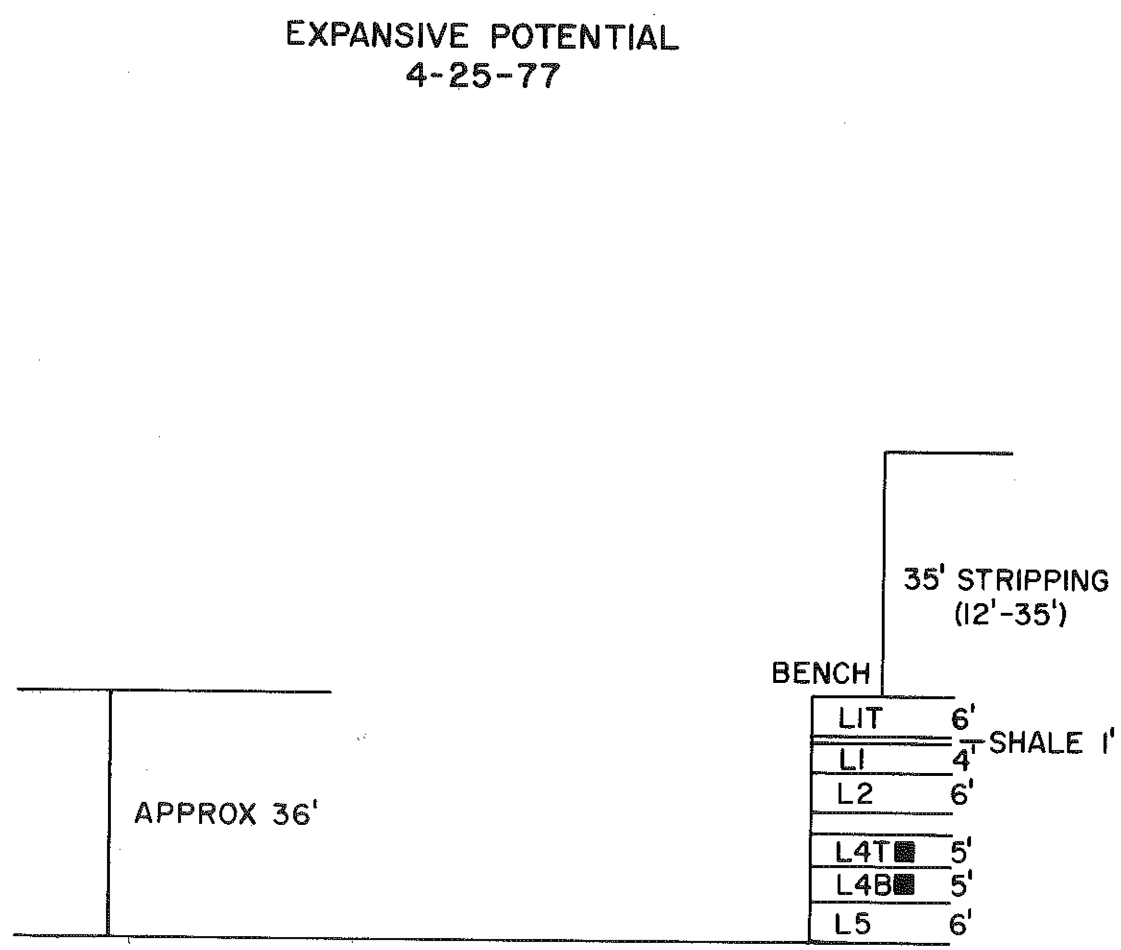


SOURCE NO. 36

EXPANSIVE POTENTIAL
4-20-77

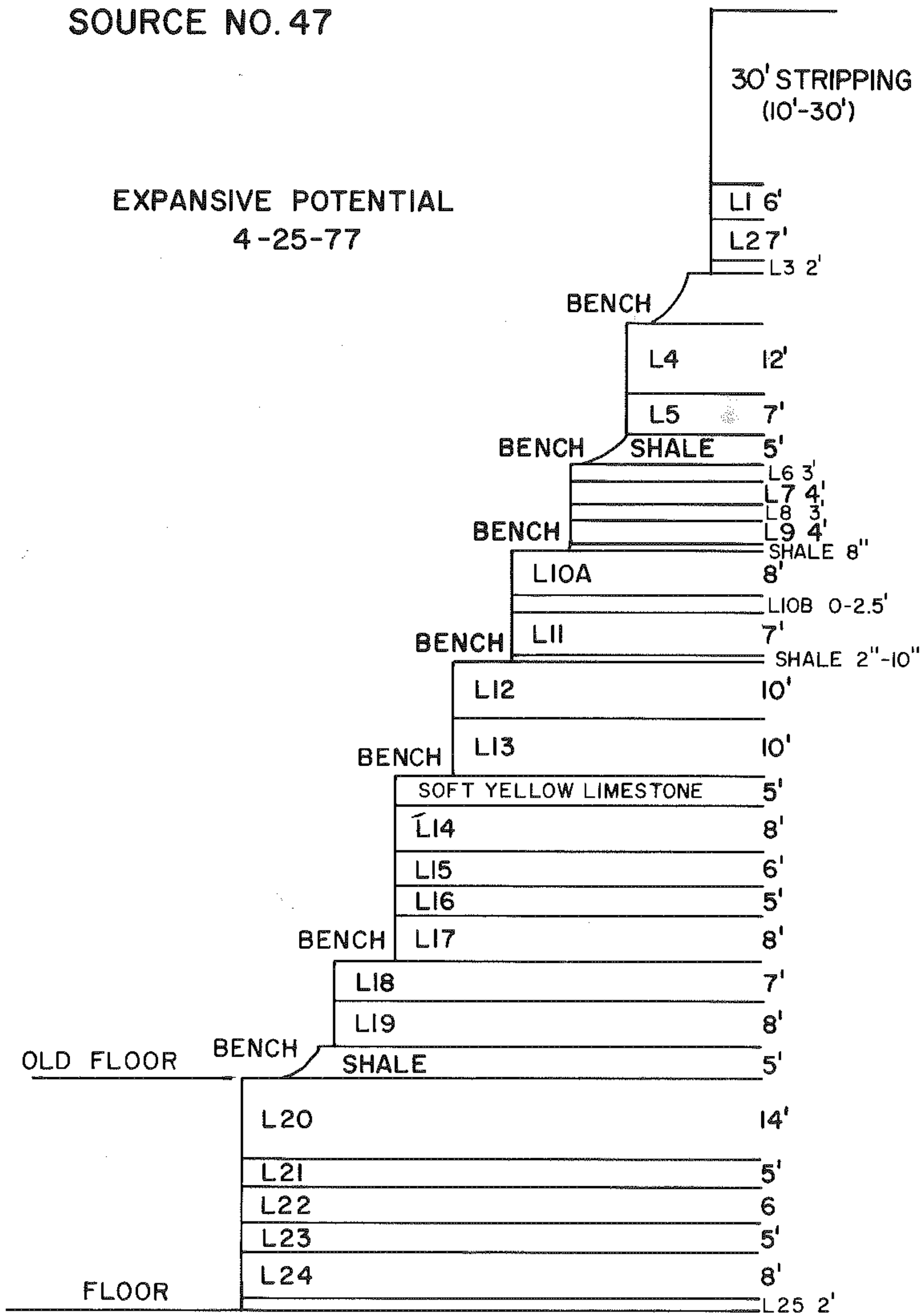


SOURCE NO. 38


EXPANSIVE POTENTIAL
4-25-77
35' STRIPPING
(12'-35')
BENCH
L1T 6'
SHALE 1'
L1 4'
L2 6'
L4T 5'
L4B 5'
L5 6'
APPROX 36'

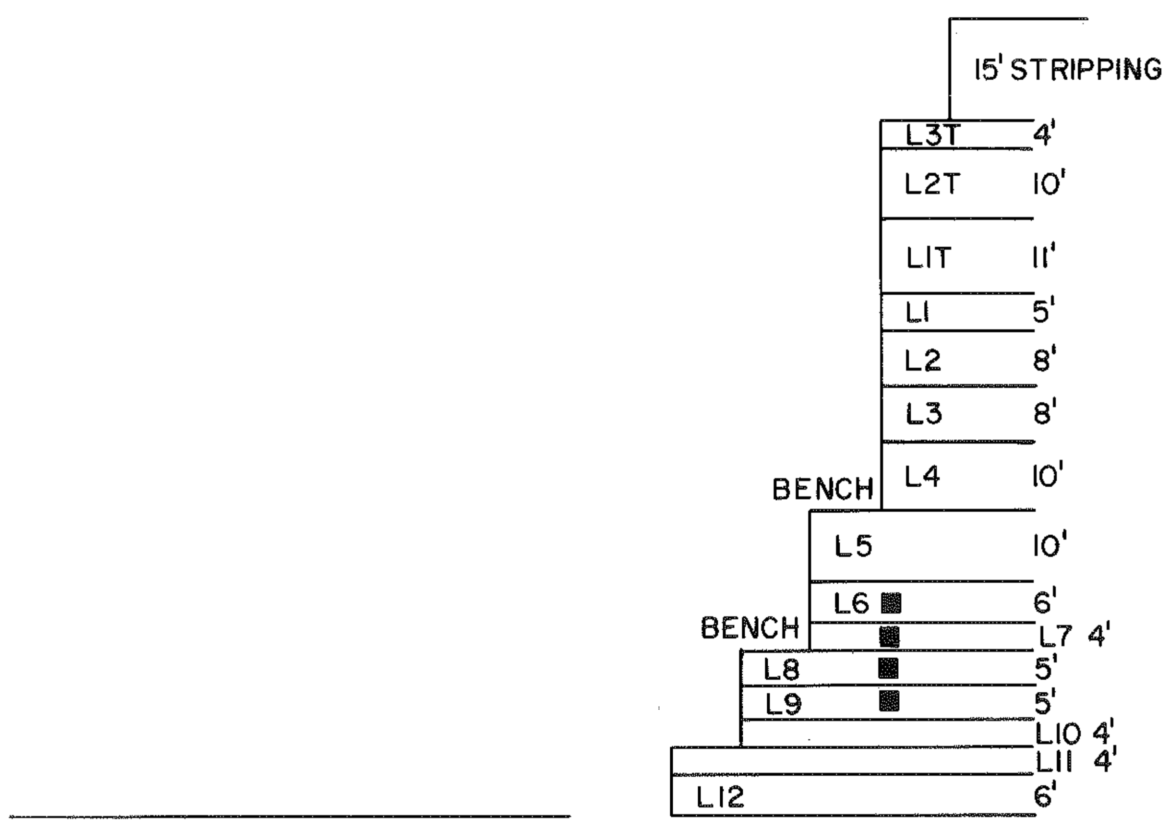
SOURCE NO. 47

EXPANSIVE POTENTIAL
4-25-77

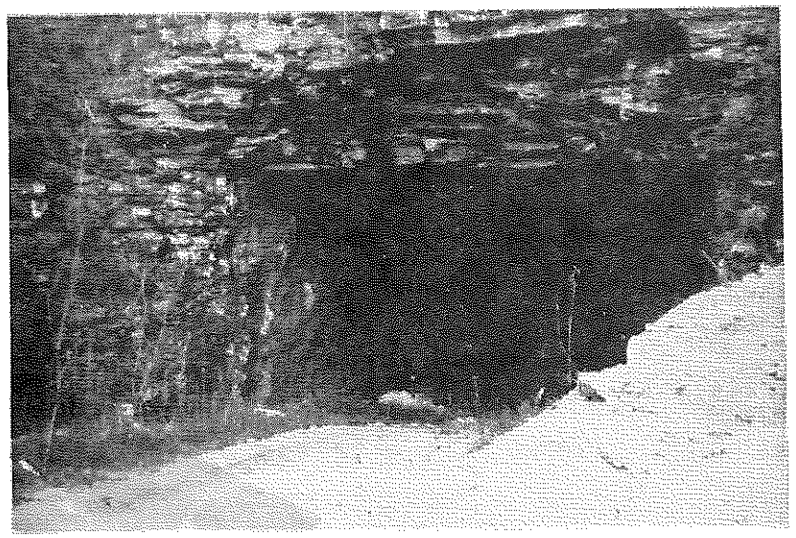


SOURCE NO. 49

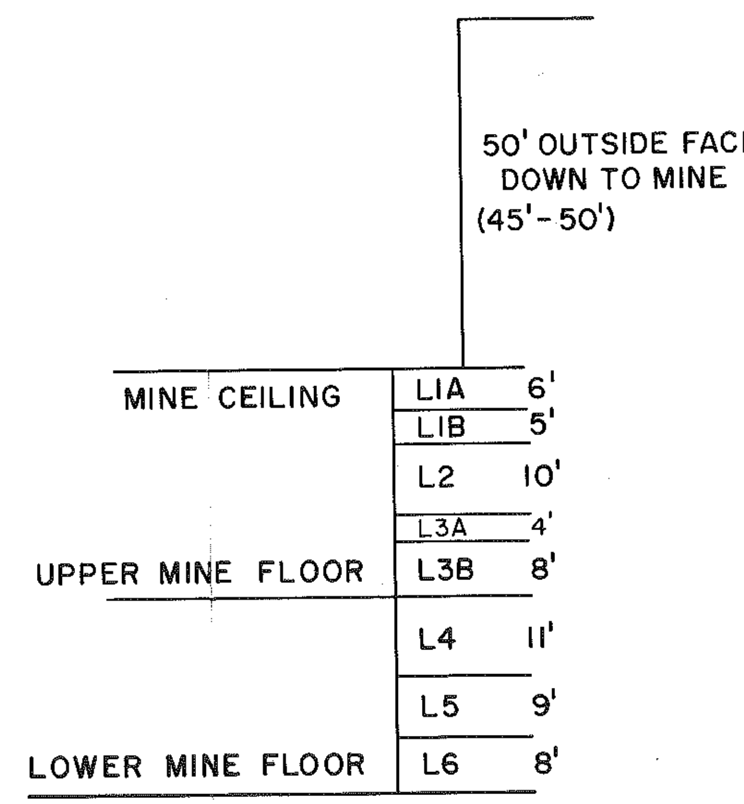
EXPANSIVE POTENTIAL
4-26-77

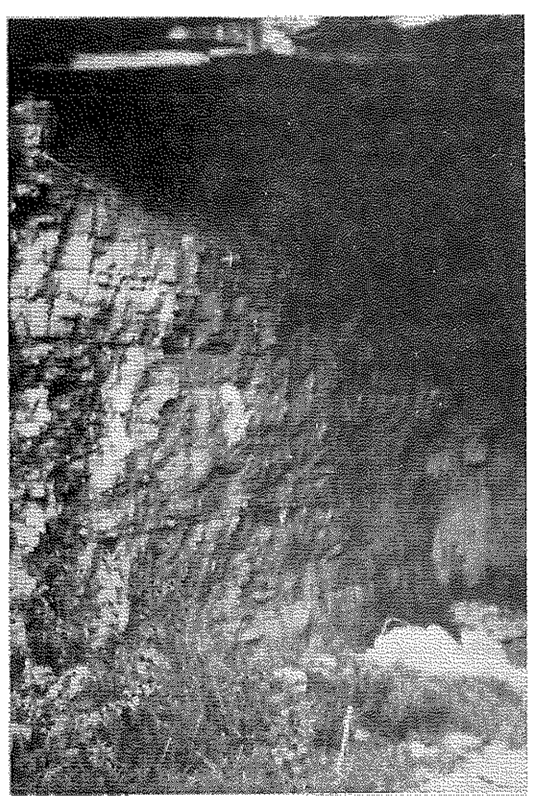


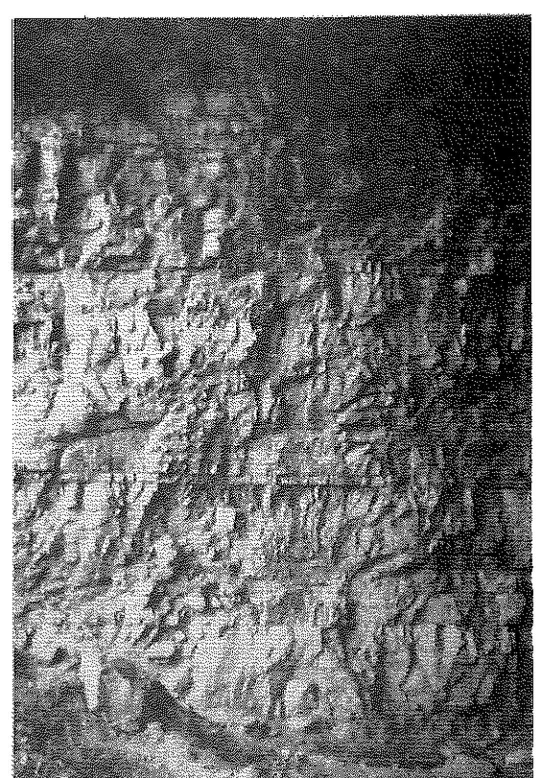
SOURCE NO. 51
HARROD & CARTER
FRANKLIN COUNTY
ORDIVICIAN AGE



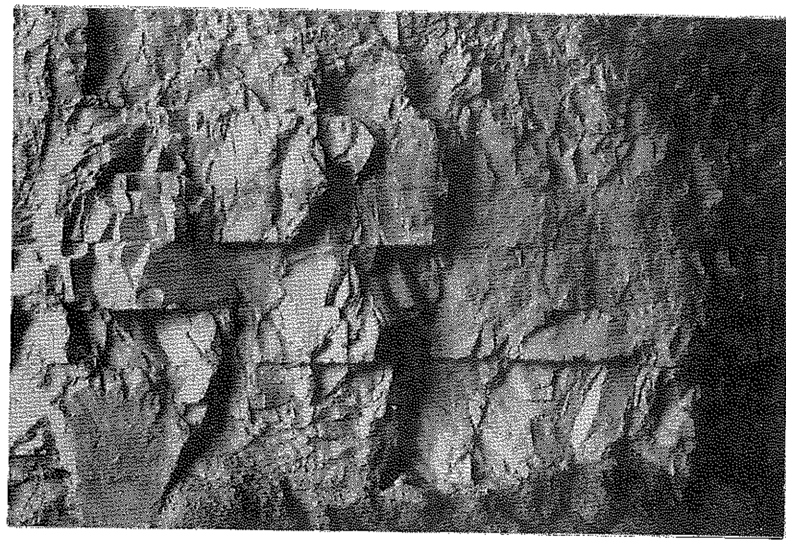
EXPANSIVE POTENTIAL
4-26-77





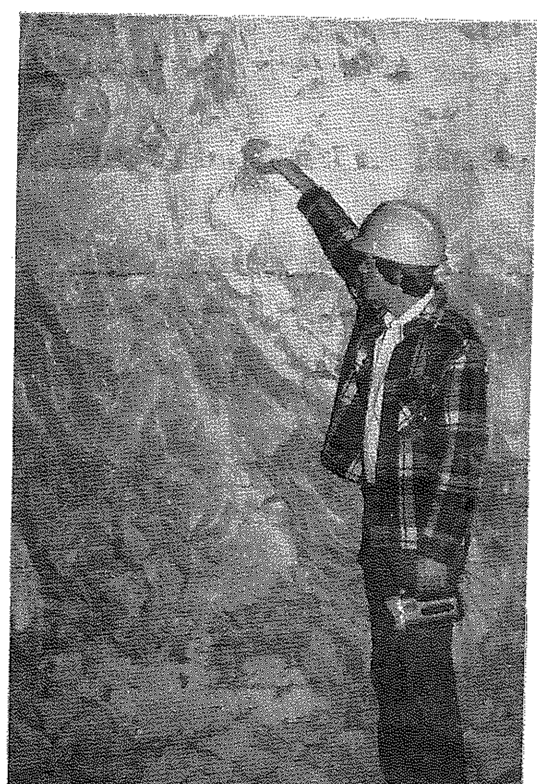


SOURCE NO. 71
CAMP NELSON STONE
GARRARD COUNTY
ORDOVICIAN AGE



L2 12'

L3 7.5'



L3 7.5'

EXPANSIVE POTENTIAL
4-20-77

50' STRIPPING
(10'-50')

38' EXPOSED TYRONE ABOVE MINE
(28'-38')
NOT TO BE USED
UNLESS RESAMPLED

MINE CEILING

L1 4'

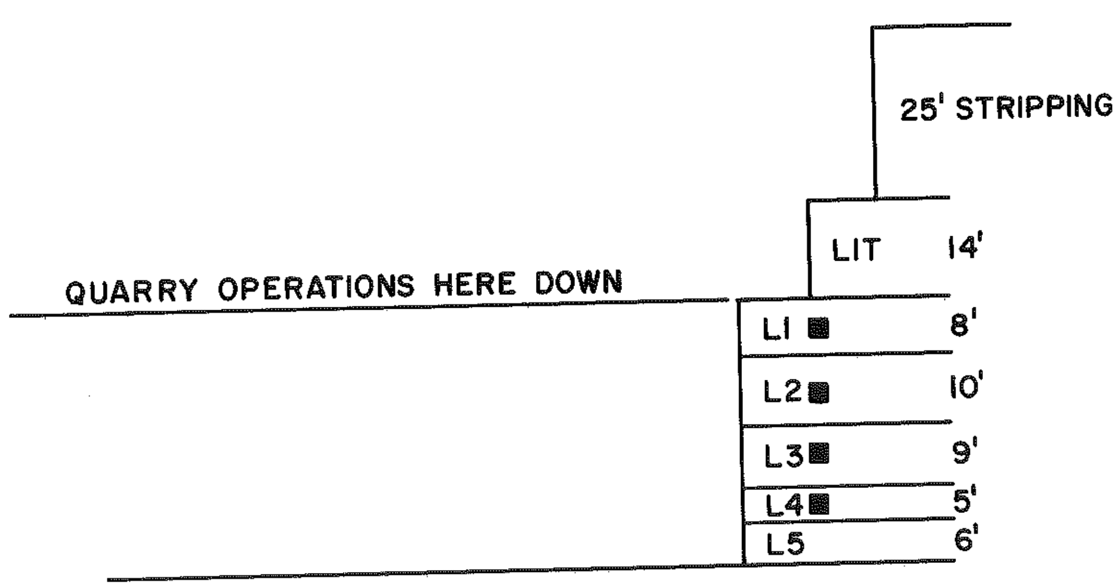
L2 12'

MINE FLOOR

L3 8'

SOURCE NO. 85

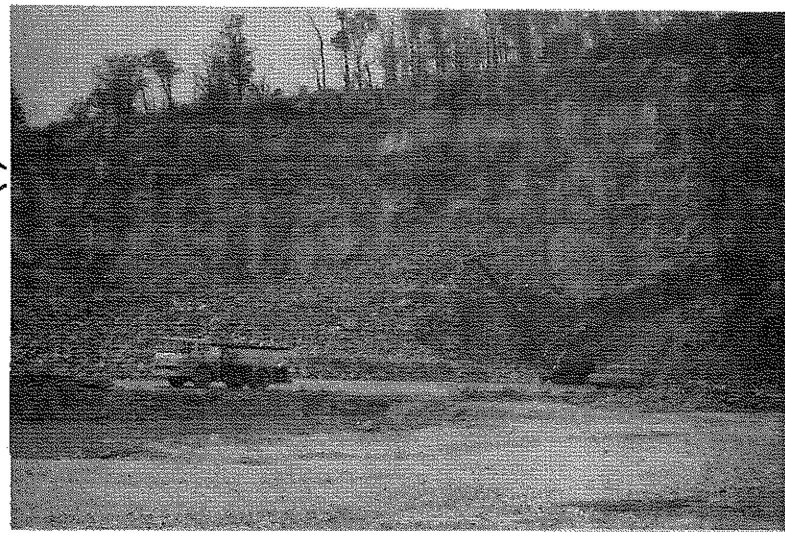
EXPANSIVE POTENTIAL
4-26-77



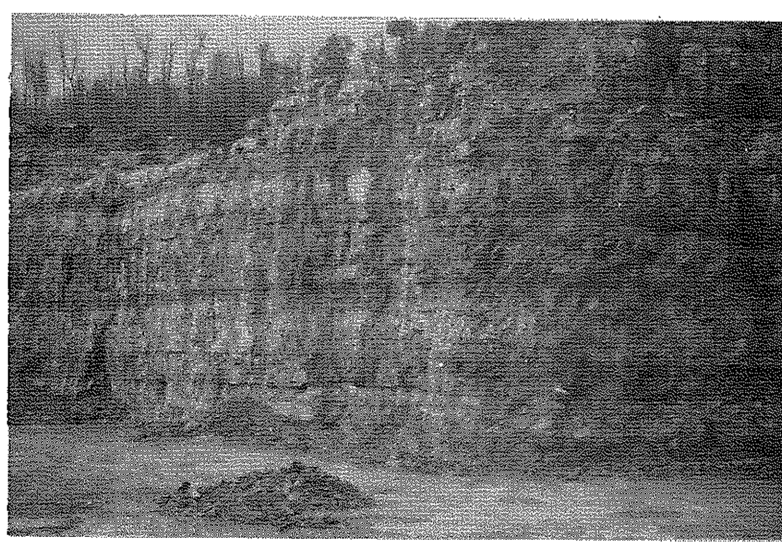
SOURCE NO. 86
SHAMROCK STONE
CLINTON COUNTY
MISSISSIPPIAN AGE

EXPANSIVE POTENTIAL
4-26-77

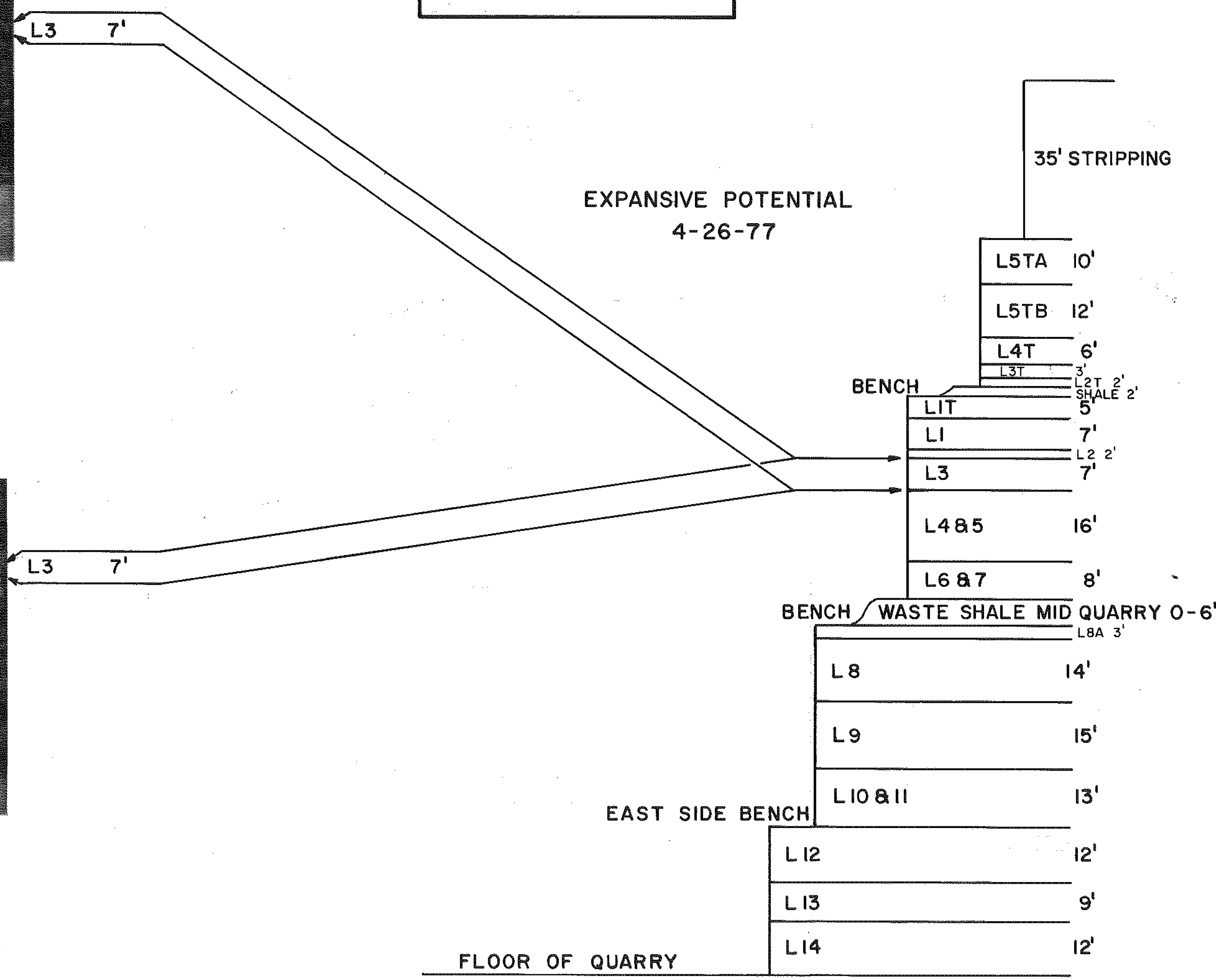
WEATHERING PROMINANT

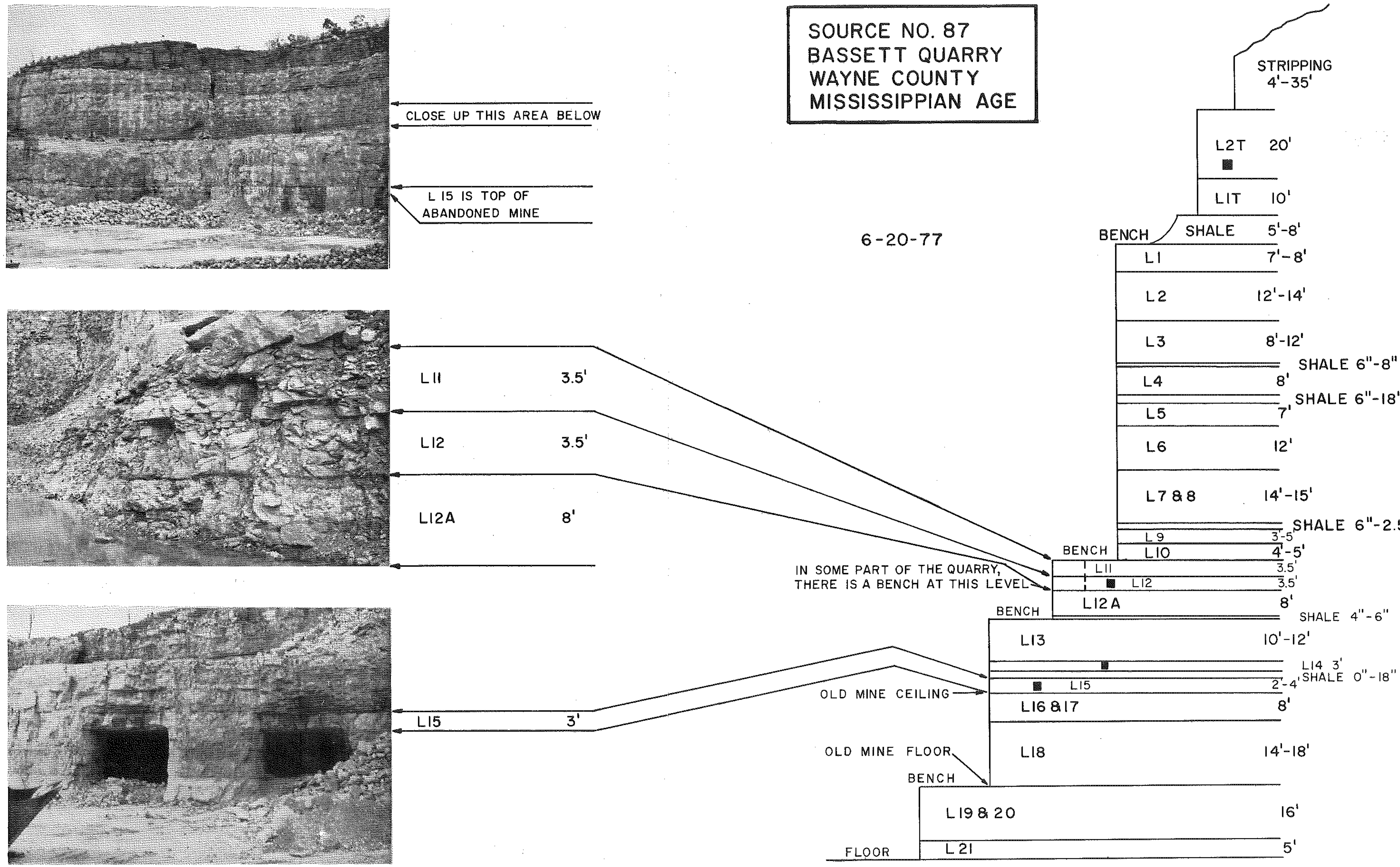


DISTANT VIEW OF QUARRY FACE - SLIGHTLY CLOSER VIEW BELOW OF ANOTHER FACE

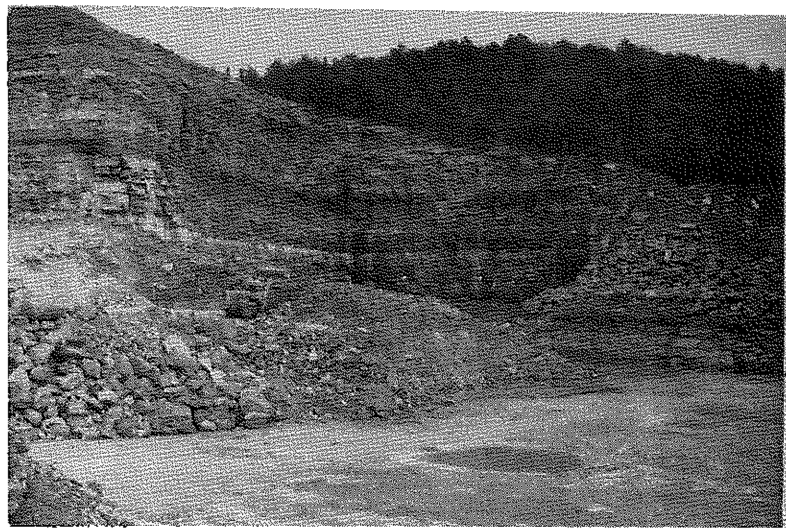


SHOWS RAPID WEATHERING IN FACE



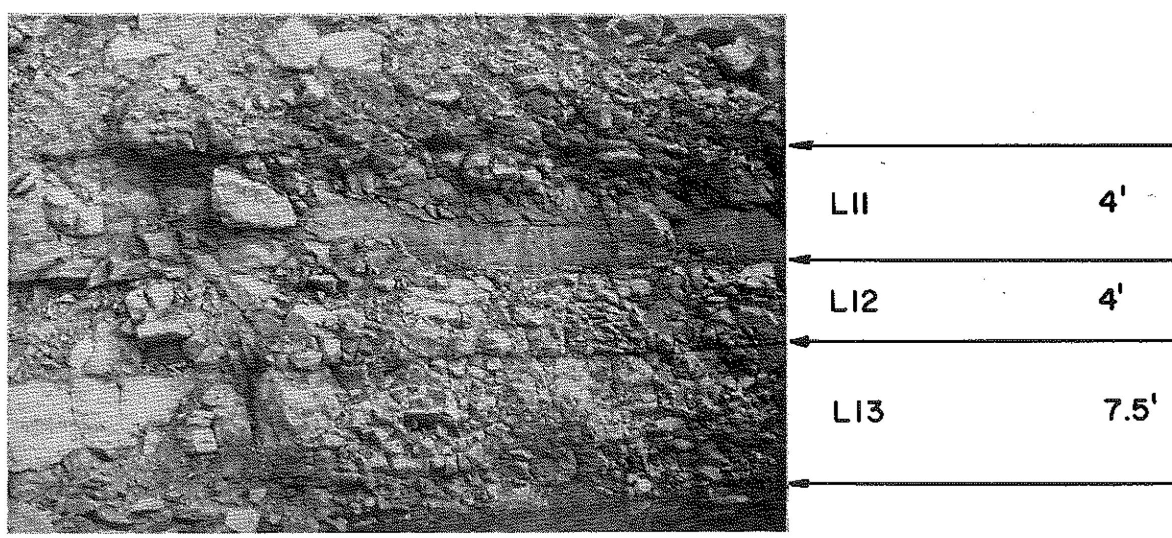

SOURCE NO. 87
BASSETT QUARRY
WAYNE COUNTY
MISSISSIPPIAN AGE
6-20-77
CLOSE UP THIS AREA BELOW
L 15 IS TOP OF ABANDONED MINE
L11 3.5'
L12 3.5'
L12A 8'
L15 3'
STRIPPING 4'-35'
L2T 20'
L1T 10'
BENCH
SHALE 5'-8'
L1 7'-8'
L2 12'-14'
L3 8'-12'
SHALE 6"-8"
L4 8'
SHALE 6"-18"
L5 7'
L6 12'
L7 & 8 14'-15'
SHALE 6"-2.5
L9 3'-5'
BENCH
L10 4'-5'
IN SOME PART OF THE QUARRY, THERE IS A BENCH AT THIS LEVEL
L11 3.5'
L12 3.5'
L12A 8'
BENCH
SHALE 4"-6"
L13 10'-12'
L14 3'
SHALE 0"-18"
L15 2'-4'
OLD MINE CEILING
L16 & 17 8'
OLD MINE FLOOR
L18 14'-18'
BENCH
L19 & 20 16'
FLOOR
L21 5'

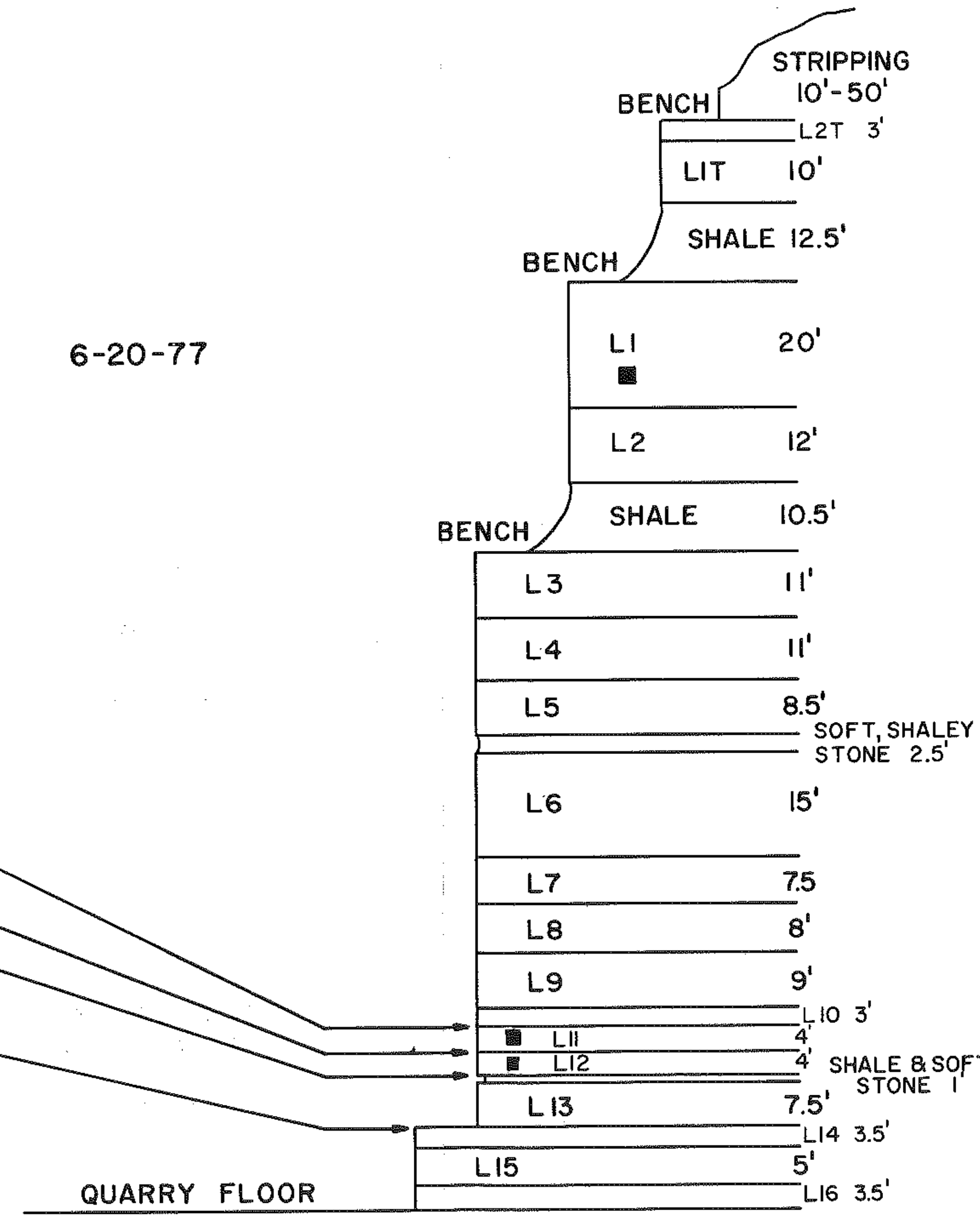
SOURCE NO. 88
STRUNK QUARRY
PULASKI COUNTY
MISSISSIPPIAN AGE



CLOSE UP THIS AREA BELOW

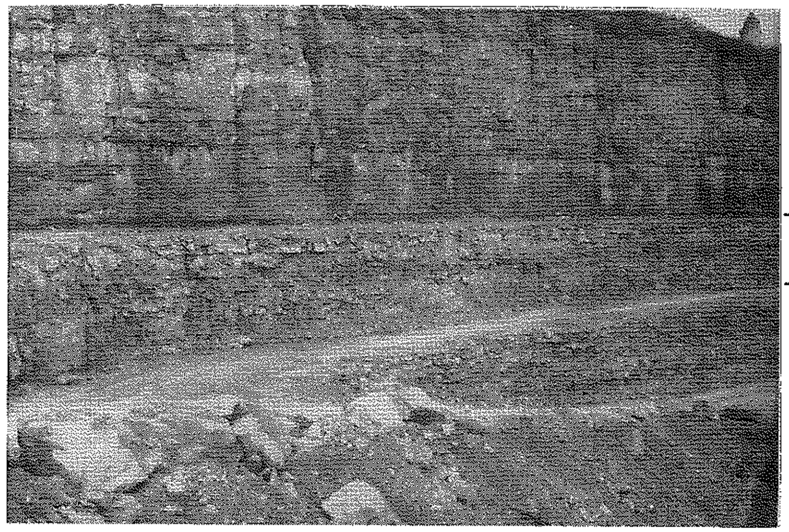
6-20-77



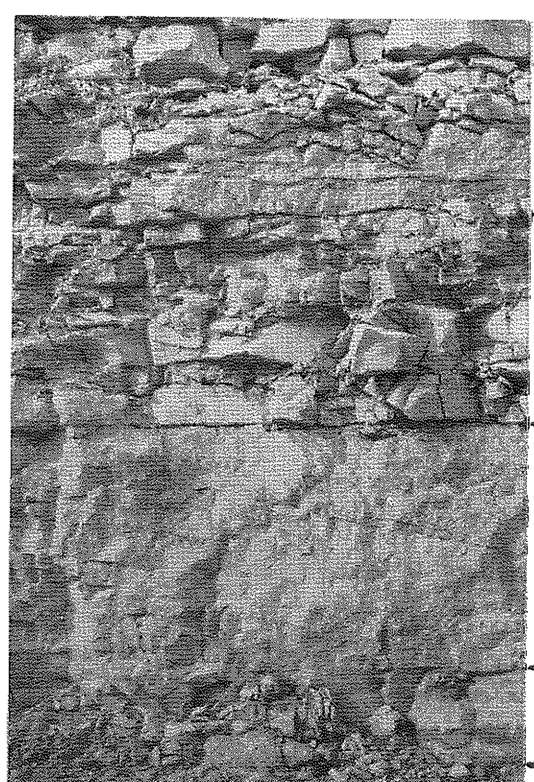


SOURCE NO. 89
SOMERSET STONE
PULASKI COUNTY
MISSISSIPPIAN AGE

6-10-77



CLOSE UP THIS AREA BELOW



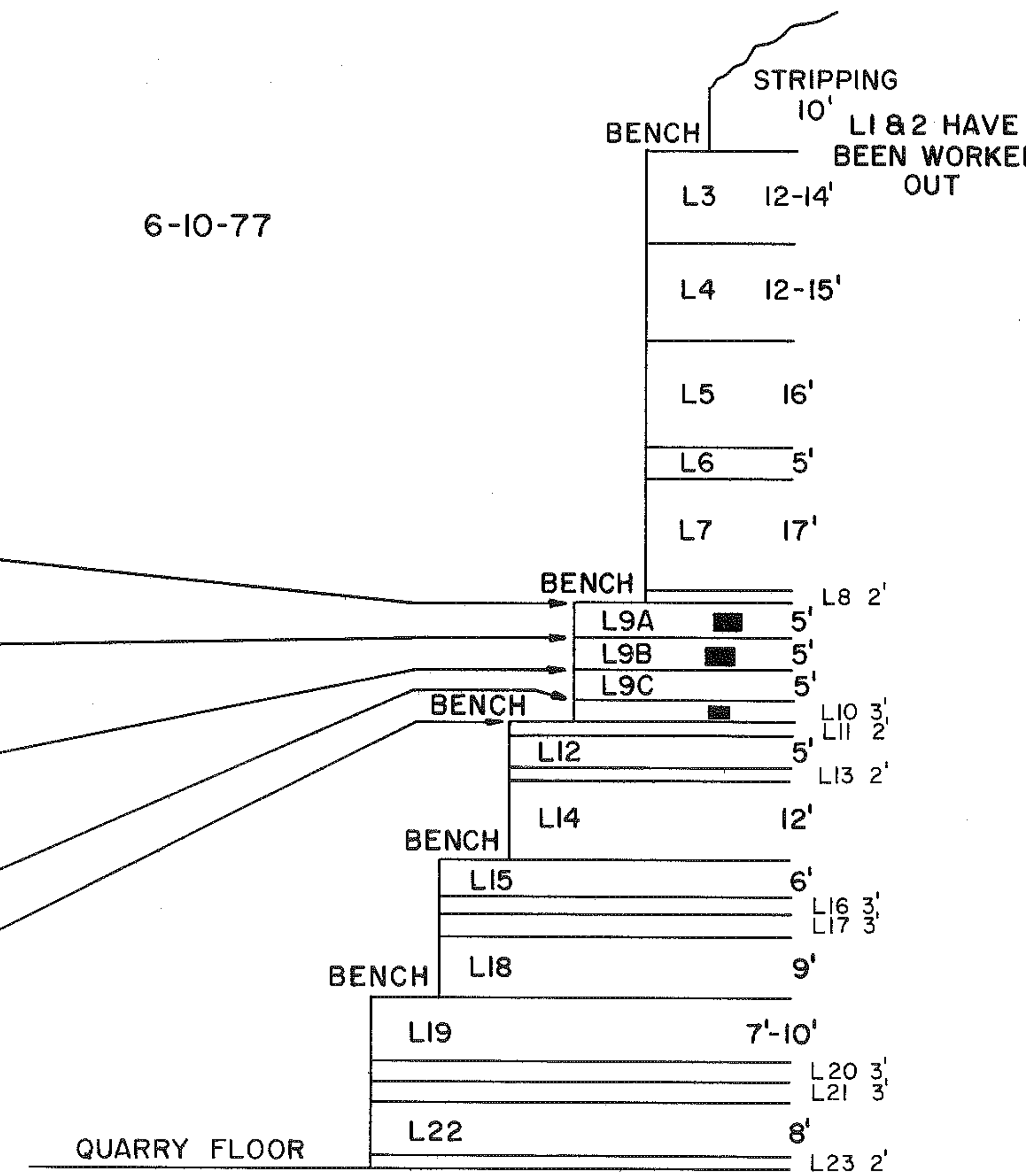
L9A 5'

L9B 5'

L9C 5'

THIS IS NONEXPANSIVE LAYER
SANDWICHED BETWEEN EXPANSIVE

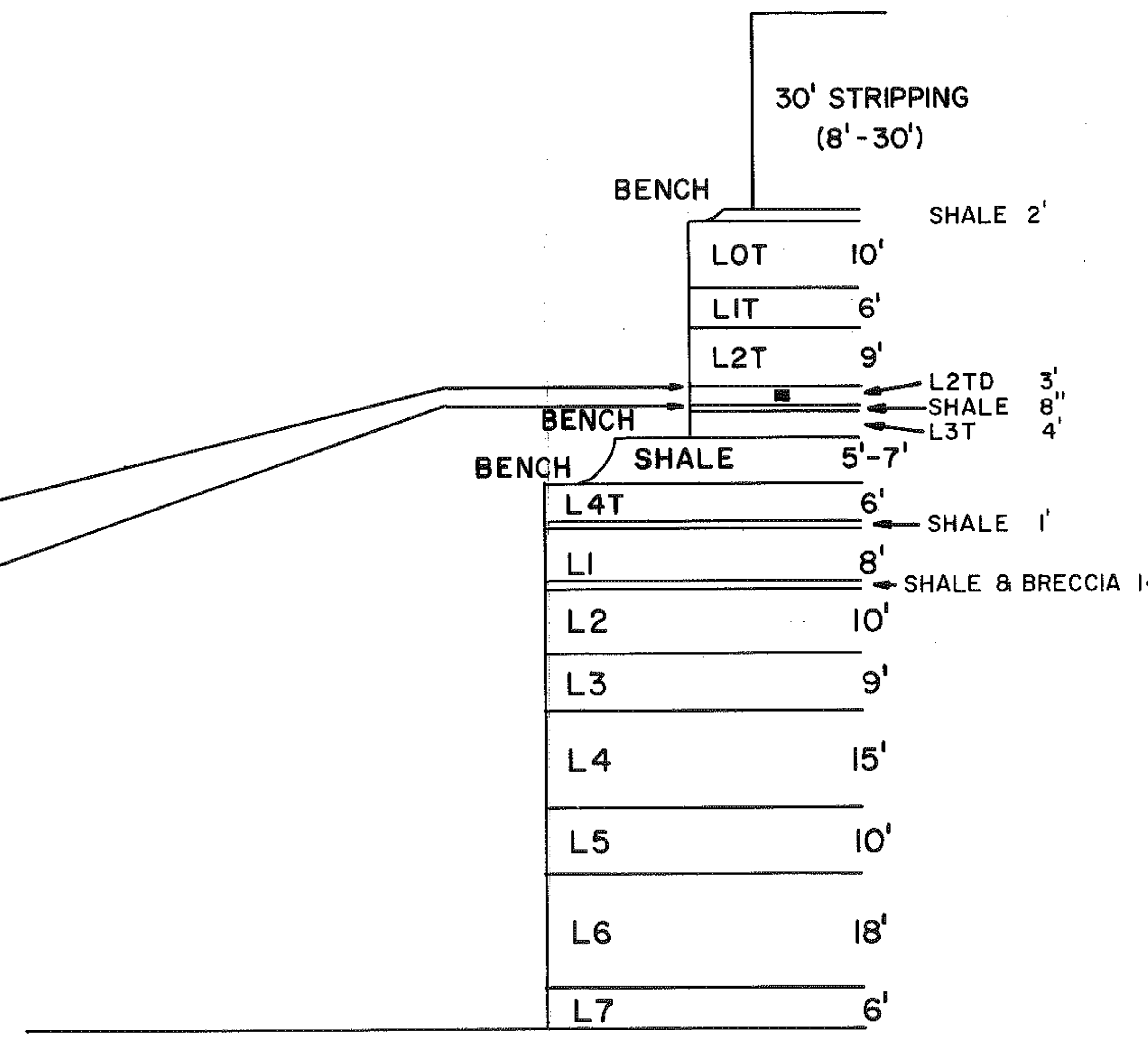
L10 3'



SOURCE NO. 94
STANDARD SLAG
CARTER COUNTY
MISSISSIPPIAN AGE

CLOSE UP THIS BENCH BELOW

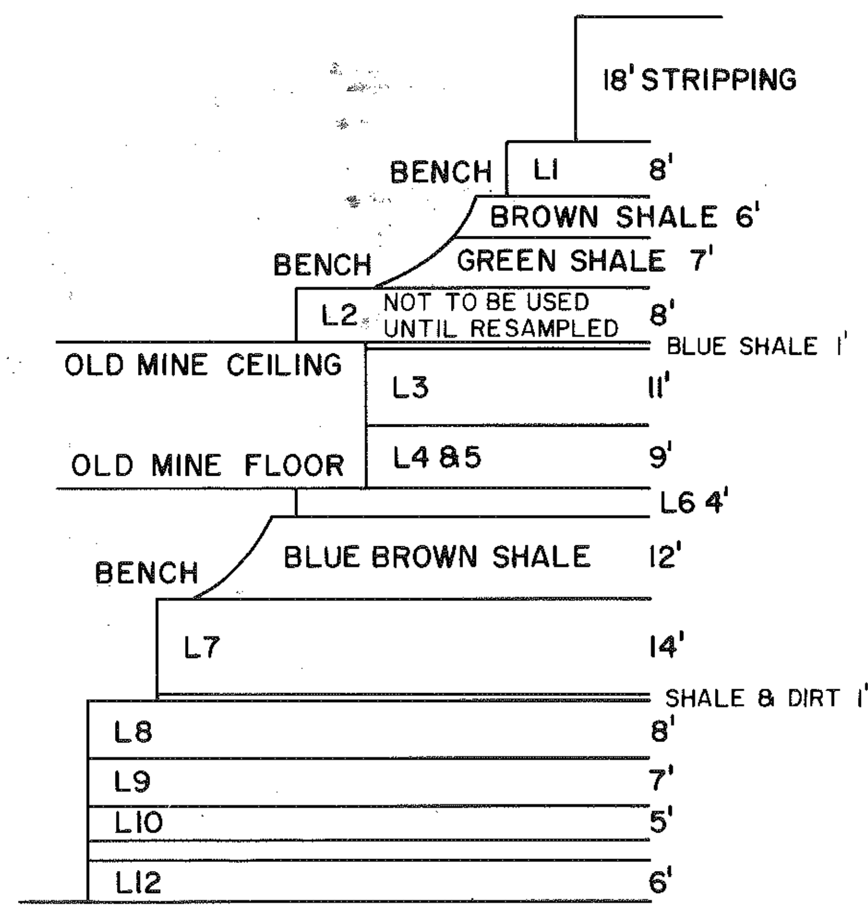
EXPANSIVE POTENTIAL
4-26-77



L2TD

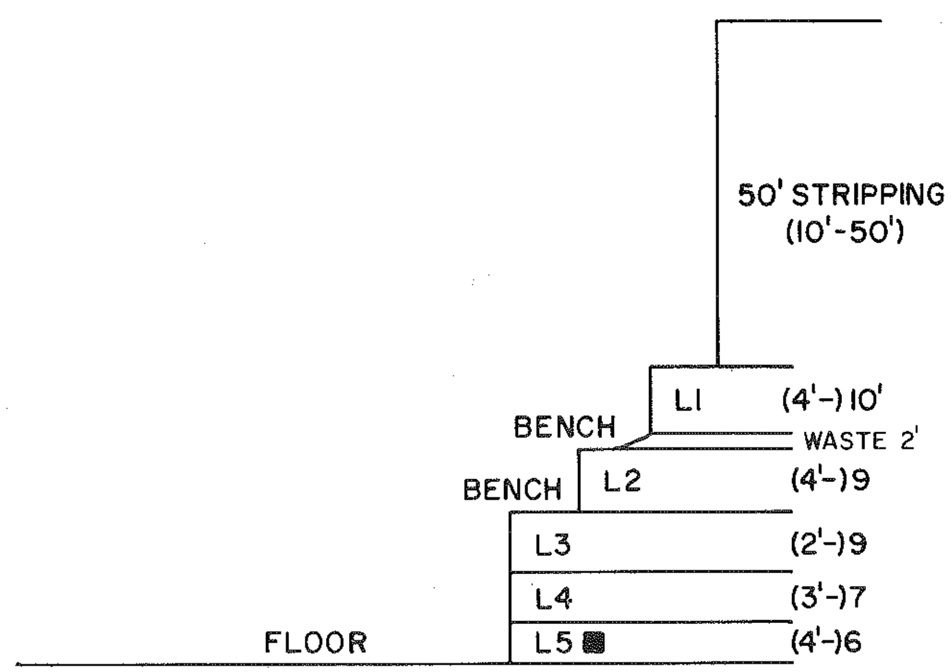
SOURCE NO. 95

EXPANSIVE POTENTIAL
4-27-77



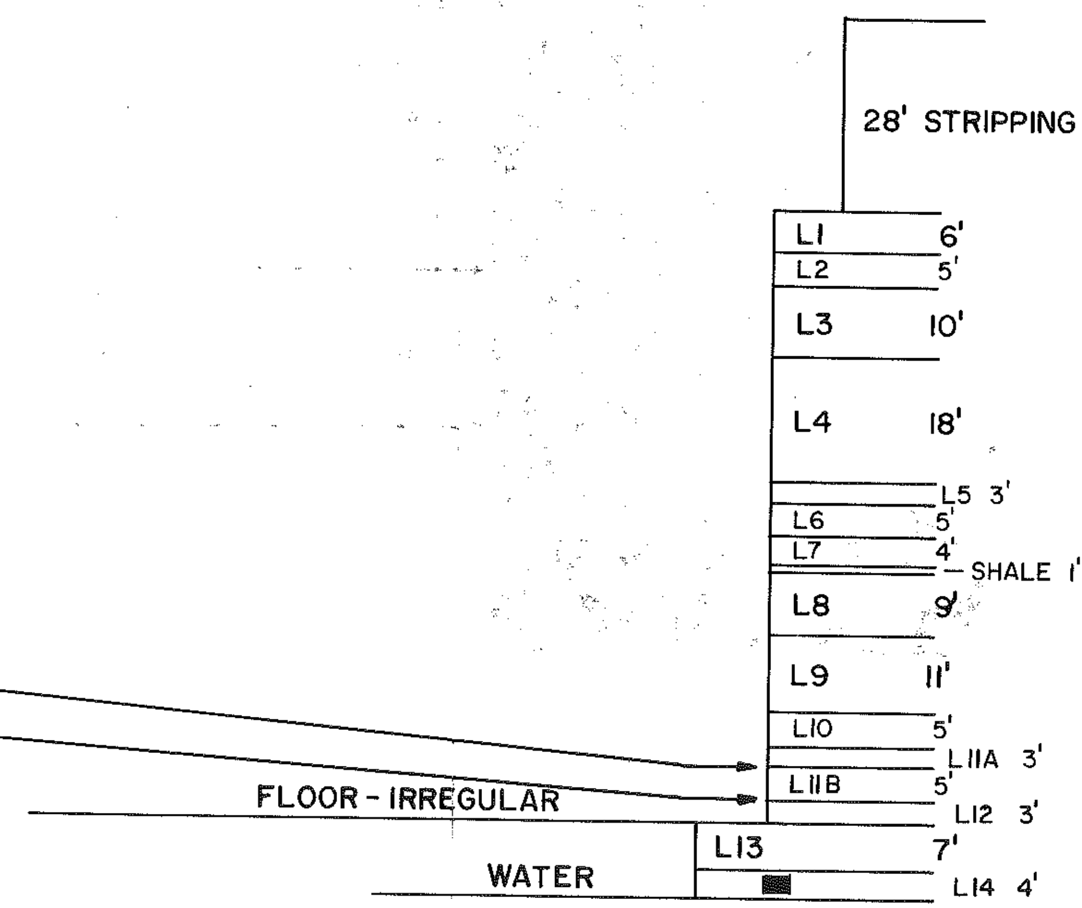
SOURCE NO. 99

EXPANSIVE POTENTIAL
4-27-77

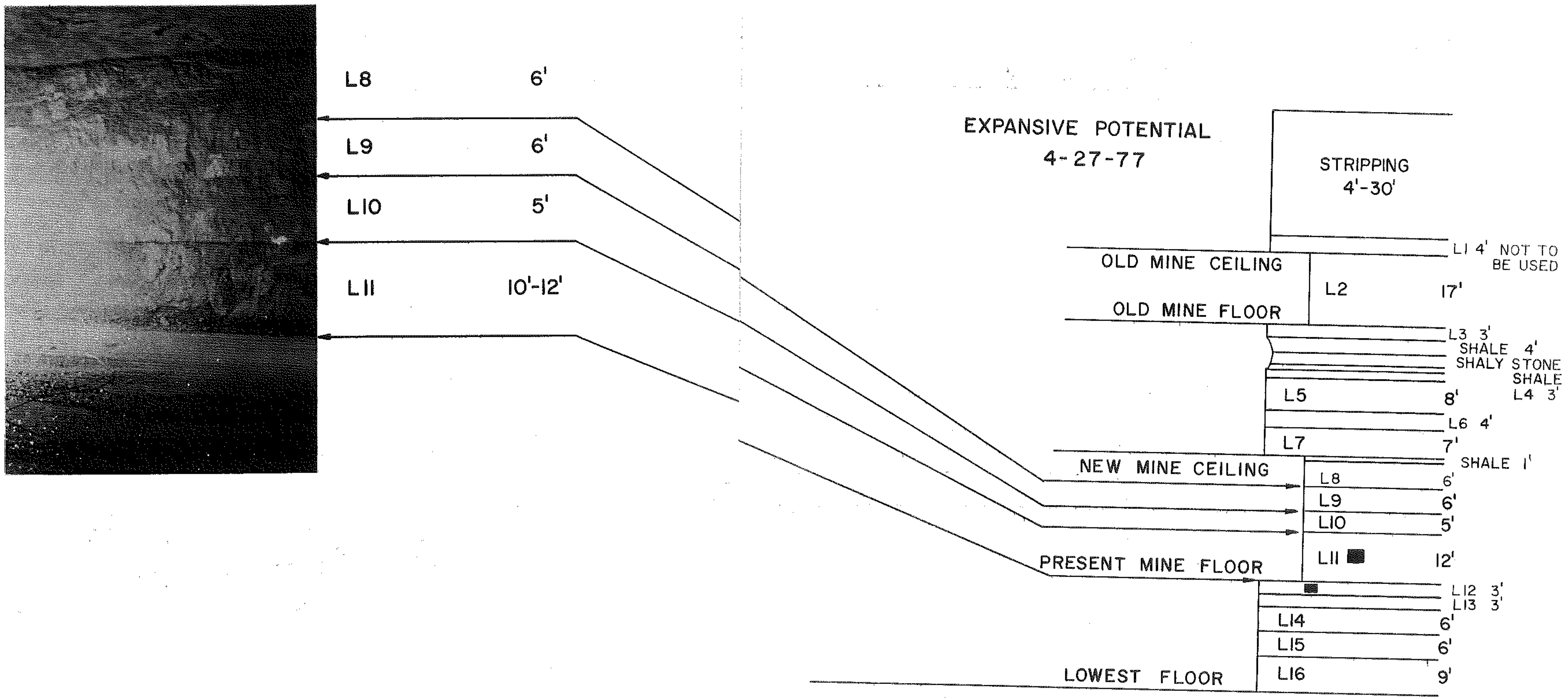


SOURCE NO. 108
NATURAL BRIDGE STONE
POWELL COUNTY

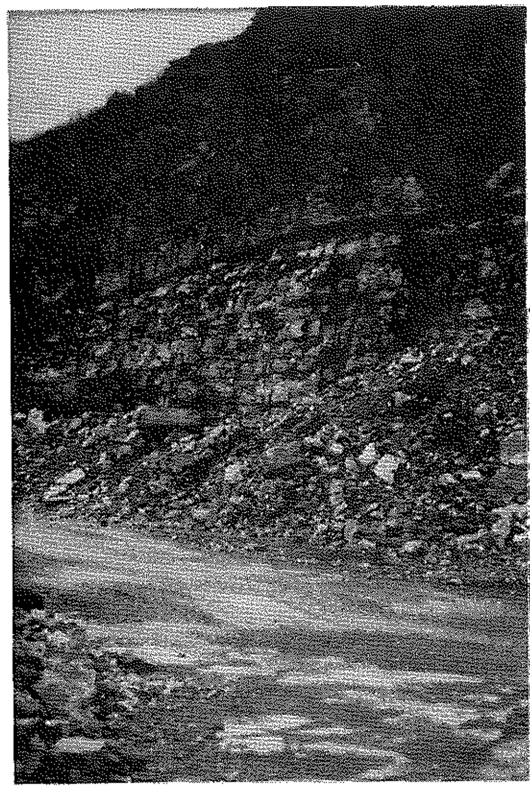
EXPANSIVE POTENTIAL
4-27-77



SOURCE NO. 116
M. A. WALKER MINE
JACKSON COUNTY
MISSISSIPPIAN AGE

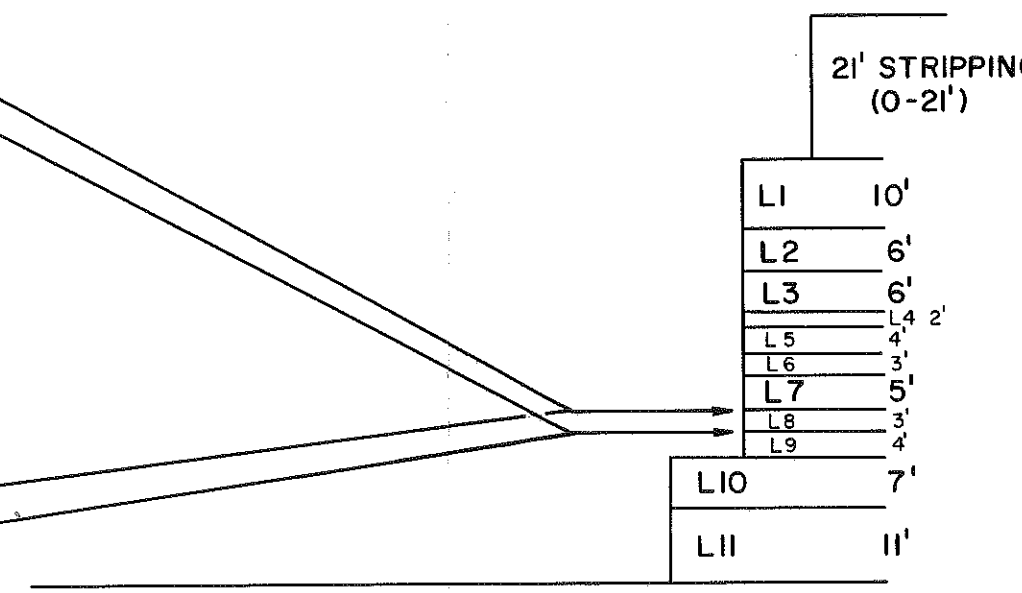


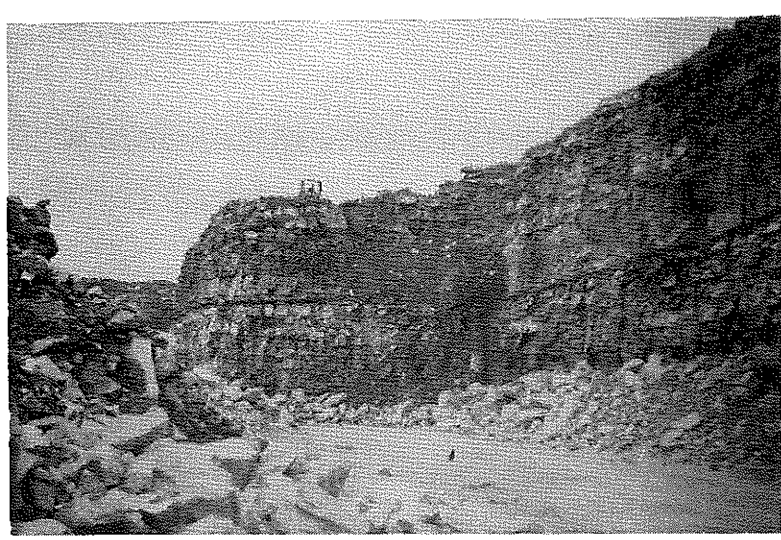
SOURCE NO 156
ALLIED MATERIALS
CHRISTIAN COUNTY
MISSISSIPPIAN AGE



L8 1'-3'

EXPANSIVE POTENTIAL
5-5-77





L8 1'-3'

SHOWS CRUMBLING
AT FAR POINT
BELOW BREAK